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Gas Adsorption/Absorption Heat Switch

Final Report of Phase I

C.K. Chan

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Air Force Space Technology Center

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DEFINITION OF MATHEMATICAL SYMBOLS

α	=	overall accommodation coefficients defined by equation (2.1.7a)
$\bar{\alpha}$	=	$\sqrt{2}\,\alpha$ cm^{-1}, equation (5.21)
β	=	parameter defined by equation (5.23)
β_1	=	parameter defined by equation (2.1.5)
	=	mean free path, cm
α_1, α_2	=	accommodation coefficients for surfaces 1 and 2, respectively
α_1, α_2	=	defined by equations (5.9a,b)
γ	=	specific heat ratio (C_p/C_v) of the gas
Γ_1, Γ_2	=	parameters defined by equations (5.23) and (5.24)
ϵ_1, ϵ_2	=	emissivity of surfaces 1 and 2, respectively
$\bar{\epsilon}$	=	effective surface emissitivy, equation (2.1.16)
ρ_p	=	bulk density of the adsorber, gm/cc
ρ_a	=	molecular density of the adsorber, gm/cc
Ω_k	=	collision function
σ_L	=	Lenard-Jones parameter, A
σ_k	=	deviation (error bound) of the variable k, dimension of σ_k is the same as k
σ_s	=	Stefan-Boltzmann Constant, W/cm^2K^4
μ	=	viscosity, poises
a,b	=	positive constants
A	=	area, cm^2
A	=	wD, 1/2 cross-sectional area of a fin, cm^2
A_{ck}	=	cross-sectional area of the inner diameter of the tube k, cm^2
A_f	=	total surface area of fins, cm^2

A_i = cross-section area of the fin i, cm^2

A_k = stainless steel cross-sectional area of gas line k, cm^2

A_L = cross sectional area of support tube, cm^2

A_1, A_2 = areas of surfaces 1 and 2, respectively, cm^2

A_1, A_2 = cross-sectional areas of hot and cold fins in section 5, respectively, cm^2

B = $\sqrt{h_C p/k_m A_i}$ or $\sqrt{h_{fm} p/k_m A_i}$ defined by equation (2.2.8), cm^{-1}

C_p = heat capacity, J/gmK

C_ℓ = mass ratio of gas being adsorbed at P_ℓ, T_ℓ, gm of gas/gm of adsorber

C_h = mass ratio of gas being adsorbed at P_h, T_h, gm of gas/gm of adsorber

ΔC = $(C_\ell - C_h)$, gm of gas/gm of adsorber

d = gap width, cm

D = width of the fin, cm

E_s = energy required to turn the switch from the off mode to the on mode, J

G = a function: Tanh (BL)/BL defined by equation (2.2.7)

G_C, G_{fm} = values of G depend on the values of h_C, h_{fm}, respectively

h_C = gap conductance when gas is continuum, W/cm^2K

h_{fm} = gap conductance when gas is in free molecular regime, W/cm^2K

I = electrical current, amp

K_C = conductance when gas is in continuum regime, W/K

K_{eq} = equivalent conductance, W/K

$\overline{K}_{eq}$ = non-dimensional conductance

k_{fm} = gas conductivity in the free molecular regime, W/cmK

K_{fm} = total gas conductance across n gaps when gas is in free molecular regime, W/K

k_g = gas conductivity in the continuum regime, W/cmK

K_g = gas conductance per unit area in the continuum regime, W/cm^2K

k_{hl} = thermal conductance of the heat link, W/K

k_k = thermal conductivity of tube k, function of temperature, W/cmK

k_L = conductivity of the support tube, W/cmK

K_L = conductance through the support tube, W/K

k_m = material conductivity, a function of temperature, W/cmK

Kn = Knudsen number

K_{OFF} = conductance when the switch is off, W/K

K_{ON} = conductance when the switch is on, W/K

K_R = conductance due to thermal radiation, W/K

k_1, k_2 = thermal conductivities of hot and cold fins, respectively, W/cmK

L = fin length, cm

L_k = length of the gas line k between two nodal points, cm

L_L = length of support tube, cm

m_a = adsorbent mass, gm

m_p = structural mass of the pump, gm

M = molecular weight, gm/gm·mole

M_{ij} = mass in Section 7, gm

i = o operational refrigerator
C cold plate
N non-operational refrigerator

j = 3 third stage
2 second stage
1 first stage

p = fin perimeter, cm

P = gas pressure, torr

P = low pressure in adsorber, torr

P_h = high pressure in adsorber, torr

Q = heat flow, W

Q = adjusted heat input, W

Q_H = heat input to the hot side of the switch, W

Q_{Li} = Heat load on cold plate at stage i, W

Q_{Oi} = Heat load of operational refrigerator at stage i, W

Q_{LP} = heat leak from the hot side, W

Q_{hs} = heat leak from pump to heat sink, W

Q_i = heat transfer between two elements, W

q_R = radiative heat flux W/cm^2

R = gas constant, its value depends on the units of pressure and temperature used in the equations

R = electrical resistance, ohms, or thermal resistance K/W

R_{Fi} = thermal resistance at stage i, between the cold plate and the non-operational refrigerator, K/W

R_H = the electrical resistance of the Dale resistor, ohms

R_k = thermal resistance of the gas line k, K/W

R_K = thermal resistance between the hot side and the cold side, K/W

R_{Ni} = thermal resistance on the side of the non-operational refrigerator at stage i, K/W

R_{Oi} = thermal resistance on the side of the operational refrigerator at stage i, K/W

R_{pi} = thermal resistance at stage, between the cold plate and the operational refrigerator, K/W

R_T = total electrical resistance, ohms

R_W = the electrical resistance of the leads from the power supply to the resistor, ohms

R_1 = thermal resistance between the hot side and the cross-shaped header, K/W

R_2 = thermal resistance between the cross-shaped header and the pump, K/W

R_3 = thermal resistance between the room temperature and the cross-shaped header, K/W

R_4 = thermal resistance between T_J and T_C, K/W

R_5 = thermal resistance between the pump and the pump base, K/W

S.R. = Switch ratio based on conductance

$(S.R.)_Q$ = Switch ratio based on heat flow

T = gas temperature, K

T_1, T_2 = temperatures of surfaces 1 and 2, respectively, K

T_1, T_2 = in Section 5 temperature distribution of the hot and cold fins, respectively, K

$T_{i,j}$ = temperature in Section 7, K

i = o operational refrigerator
C cold plate
N non-operational refrigerator

j = 3 third stage
2 second stage
1 first stage

T_{av} = average temperature, K

T_e = room temperature, K

T_ℓ = low temperature of the adsorber, K

T_h = high temperature of the adsorber, K

T_H, T_C = temperatures of the hot and cold side, respectively, K

T_J = temperatures at the cross-shaped header, K

T_p = temperature of the pump, K

T_s = temperature of the pump base, K

ΔT = temperature difference, K

Δu = heat of desorption, J/gm

u,v = dependent parameters

V = the measured voltage, volts

V_f = gas volume between the gaps in the heat switch, cm^3

V_l = gas volume in the line and in the system, cm^3

V_p = gas volume in the adsorber, cm^3

V_g = total gas volume, cm^3

w = half of the fin thickness, cm

x = dependent variable

x = in Section 5 linear coordinate along the fin, cm

<u>Subscripts</u>

a = absorbent

C = cold side

C = continuum
fm = free molecular

g = gas

h = high

hs = heat link

H = hot side

i = i_{th} pair of fins

ℓ = low

l = line

L = support

ON	=	on mode
OFF	=	off mode
p	=	pump structure
R	=	radiation
1,2	=	surfaces 1 and 2 or hot and cold fins

EXECUTIVE SUMMARY

The service life and/or reliability of far-infrared sensors on surveillance satellites is presently limited by the cryocooler. The life and/or reliability, however, can be extended by using redundant cryocoolers. To reduce parasitic heat leak, each stage of the inactive redundant cryocooler must be thermally isolated from the optical system, while each stage of the active cryocooler must be thermally connected to the system. The thermal break or the thermal contact can be controlled by heat switches. Among different physical mechanisms for heat switching, mechanically actuated heat switches tend to have low reliability and, furthermore, require a large contact force. Magnetoresistive heat switches are, except at very low temperatures, of very low efficiency. Heat switches operated by the heat pipe principle usually require a long response time. A sealed gas gap heat switch operated by an adsorption pump has no mechanical motion and should provide the reliability and long lifetime which are required in long-term space missions. Another potential application of the heat switch is the thermal isolation of the optical plane during decontamination.

This publication presents the invention of a self-actuated heat switch system and the design, analyses, fabrication, and test data of a novel gas gap heat switch which is comprised of two finned sections separated by a gap. The heat switch has a large heat transfer area in a small volume. The switch is operated by a gas adsorption pump which, when heated, desorbs and supplies gas to the gap, thus allowing heat transfer across the gap and turning the switch on. The pump, when cooled, adsorbs and removes the gas from the gap, thus turning the switch OFF. When implemented with redundant refrigeration systems for thermal isolation and connection, the switch can be self-actuating, without any need for external control or power supply.

The conductive heat transfer across the gap in the heat switch depends on the gas pressure from the adsorption pump. During the on mode, the gas is in the continuum and has high conductivity. However, when the gas pressure is low during the off mode, the gas is in the free molecular regime and the conductivity decreases with pressure. This conductive heat transfer is coupled with the radiative heat transfer across the gaps between fins and between the support tube and the fins. Analytical models and computer codes were developed to evaluate various designs of the heat switch and the adsorption pump. A wide spectrum of design parameters, such as the geometry and the material of the heat switch, support tube and adsorption pump was analyzed. Based on these analyses, a cylindrical copper heat switch which was 2 inches in diameter and 1.5 inches in length consisting of straight fins operated by a charcoal pump, was selected for fabrication and experimental tests.

The test apparatus was designed to measure the temperatures and the heat flow and, hence, the conductance when the switch was on and off at temperature ranges of 10 K, 20 K, and 80 K. The heat switch and the pump were suspended inside a vacuum vessel. The cold side of the switch was thermally grounded to the liquid cryogen temperature at the heat sink base. The cryogen for the 80 K tests was liquid nitrogen and for other test temperatures it was liquid helium. The heat switch pump, which was thermally linked to a separate dewar, could be operated at 10 K, while the cold side of the heat switch could be operated at 10 K, 20 K, and 80 K to simulate the actual system configuration. There were heaters and thermal sensors attached at the hot side and the cold side of the heat switch, as well as at the pump and its heat sink base. These heaters were used to control the temperatures of the four different regions: the hot side and the cold side of the heat switch, the adsorption pump, and the pump base. The temperatures were controlled by a minicomputer which was part of the automated data acquisition system.

The switch was tested at cryogenic temperatures from 80 K down to 4 K. The heat flow and the temperature difference between the hot and the cold sides of the switch were measured at a steady state. The first series of tests involved the heat switch with no adsorption pump. The heat transfer rate was firstly determined when the switch was filled with hydrogen gas and when the switch was evacuated. The adsorption pump was then installed and the switch was turned on and off by controlling the pump temperature. The second series of tests involved the adsorption pumps with different gas loading of three different gases (hydrogen, nitrogen, and neon). These first two series of tests were performed when the cold side of the heat switch was thermally grounded to liquid nitrogen in the 80 K range. Among the gases being tested, helium was found to have the best performance if a heat sink of 10 K was available. The third series of tests simulated the operational conditions of the self-actuated heat switch where the pump was cooled to about 10 K during the off mode, while the switch temperatures were at 10K, 20 K and 80 K. Error analysis was performed to determine the error bounds of data. The heat leak from the heat switch was calculated and was used to adjust the power input data and, hence, determine the true heat flow through the switch. The test data showed that the switch ratios of the on conductance over the off conductance increased with decreasing temperatures. For the present design, a ratio of over 10,000 and a heat flow of 2 watt across a temperature difference of 0.5 K were obtained at 8 K with helium as the working gas.

Two analytical models were developed to predict the heat transfer rate when the switch was on and when it was off. The thermal network approach was used for the computer code HTSWCH where the conduction and the radiation across the gap were decoupled. The second model considered the interaction between the conduction and the radiation at the gap. The closed-form solution of the second model, which gave physical insights into the effects of the design parameters of the fins, and the surface emissivities on the switch performance could be used in design optimization.

Due to the low system temperature in the present study, the conduction and the radiation were not strongly coupled. Hence, the numerical values of the closed-form solution compared well with the solution given by the thermal network. The test data also compared well with the numerical predictions as:

Temperature	On Conductance(W/K)		Off Conductance(W/K)		Switch Ratio	
	Exp.	Analytical	Exp.	Analytical	Exp.	Analytical
10 K	4.9	4.9	4.50E-4	4.80E-4	10900	10208
20 K	8.0	7.5	1.07E-3	1.20E-3	7500	6300
80 K	11	13	4.90E-3	6.40E-3	2245	2301

Both the data and the analyses showed that at 80 K, the conductance during the 'OFF' mode, and hence the switch ratio, were limited by both thermal radiation and conduction through the support tube. At temperatures below 20 K, the support tube conductance was the only limiting factor. By improving the thermal resistance of the support tube, and by reducing surface fin emissivity, heat switch ratios up to 30,000 could be achieved.

The interface of the heat switch with two redundant coolers was then analyzed. Depending on the system objective, it may be advantageous to have a heat switch with low switch ratio at the first and second stages, so there is less temperature difference at the coldest stage.

1.0 INTRODUCTION

1.1 Thermal Switching in Space

Far infrared sensors on future surveillance satellites must have focal planes and optical elements cooled to cryogenic temperatures. At present, mechanical cryocoolers for these sensors and optics are major life-limiting components of these surveillance satellites [1.1]*. One way to extend the useful life of these sensors and, hence, of the satellites is to use redundant cryocoolers [1.2]. To reduce parasitic heat loss, each stage of an inactive redundant cryocooler needs to be thermally isolated from the optical system, while each stage of the active cryocooler needs to be thermally connected to the system. This making or breaking of thermal contacts between two regions can be accomplished by heat switches as shown in Fig. 1.1 [1.3, 1.4]. The cold plate temperatures, the heat loads, and the temperature differences between the cold plate and the cold finger for a three-stage system are:

	Cold Plate Temperature	Heat Flow	Temperature Difference Between Cold Plate and Cold Finger
First Stage	85 K	70 to 100 watts	$\Delta T = 5$ K
Second Stage	22 K	20 watts	$\Delta T = 2$ K to 5 K
Third Stage	9 K	2 watts	$\Delta T = 1$ K with 0.1 K to 0.5 K stability

The cold finger temperatures in Fig. 1.1 correspond to the temperatures when the refrigerator is operational. When the refrigerator is not functioning, the cold finger temperatures would be raised depending on the heat leaks of the entire system. It is the function of the heat switch system to thermally connect the cold plates to the cold fingers of the operational refrigerator, and to thermally isolate the non-operational refrigerator from the cold plates to reduce parasitic heat loss.

The switch can be used to thermally isolate the optical plane from an operating refrigerator during the decontamination period when the optical plane has to be heated up to remove contaminants which have collected on the sensor or the optics during cryogenic operation. This temperature control function is not limited to cryocoolers with cold fingers, such as the Stirling and Vuilleumier, but is also applied to the reversed Brayton cryocooler, or the solid or liquid cryostats when it may take too long to shut down and to start up the cryocooler just for the decontamination process.

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* Number in [ ] refers to reference number in Section 9.0

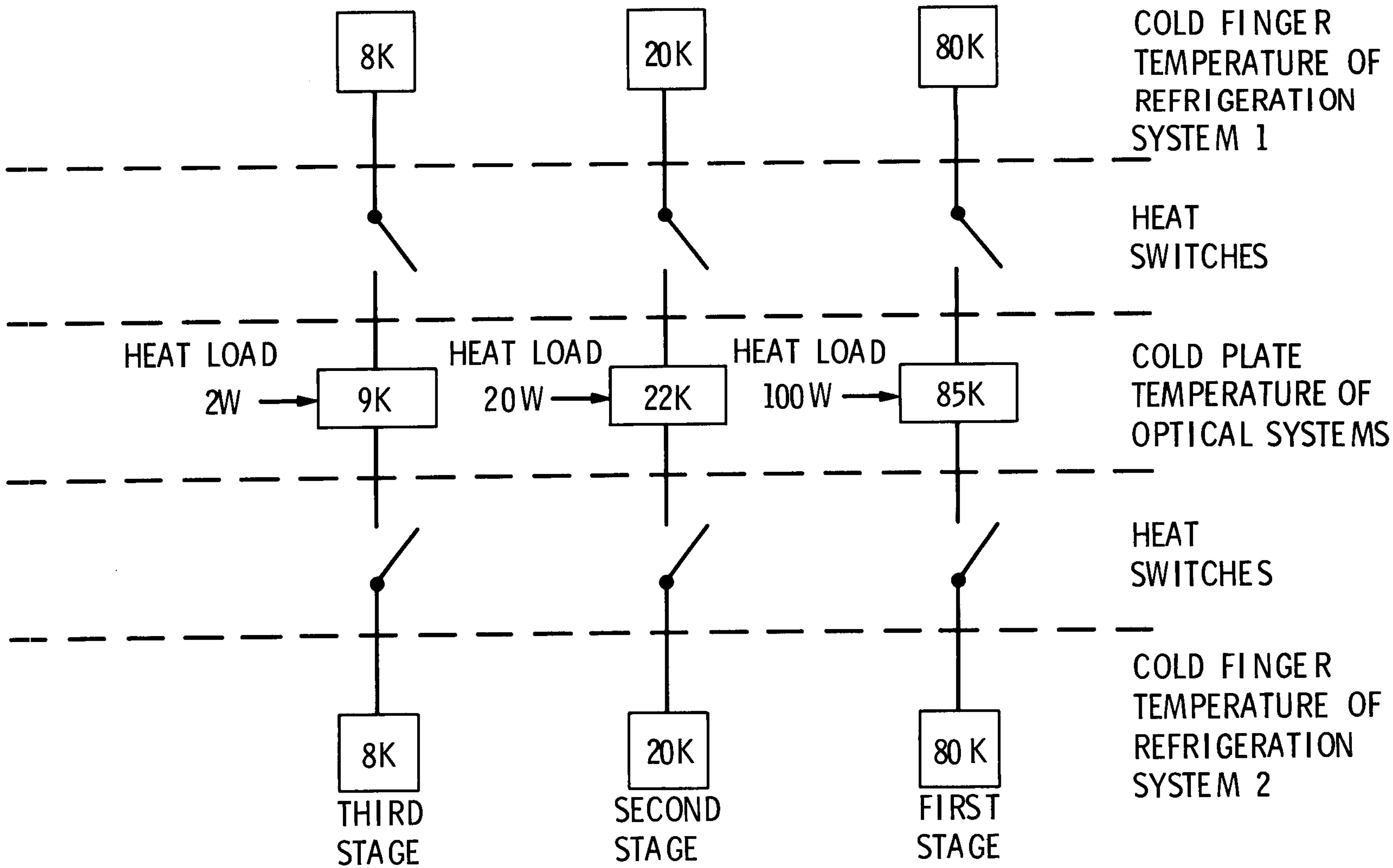

Figure 1.1. Temperatures and Heat Load Requirements of Heat Switches at Three Cryogenic Temperature Levels

During periods when data collection is not required, heat switching can be used to save energy and to prolong the useful life of solid or liquid cryogens in space by decoupling the sensor from the cryostat [1.5].

In some of the advanced cryocooler concepts, such as magnetic refrigeration [1.6] and gas sorption refrigeration [1.7], heat switches are the critical components in controlling the heat flow into and out of the paramagnetic salt or the porous sorbent bed.

1.2 Previous Thermal Switch Concepts

Several diverse approaches have been explored for thermal load switching at temperatures ranging from 300 K to 1 K. Mechanical heat switches are based on the contact of two mating surfaces under the influence of the mechanical force. There have been some concerns about the problems of diffusion bonding [1.4, 1.8] and contact pressure [1.9] and, hence, the reliability [1.10].

Another type of heat switch is based on a change in thermal conductivity of a single gallium crystal as the transverse magnetic field is increased [1.11]. This magnetic switching effect diminished rapidly as the crystal temperature was raised above 5 K, and thus the gallium was initially useful only at liquid helium temperature. Later, by using gallium and tungsten, the temperature limit was raised to 10 K. By using beryllium, the thermal conductivity was changed by three orders of magnitude by using a magnetic field of 12 kG at temperatures below 30 K [1.12]. That is equivalent to a change in thermal conductivity from that of high-purity copper to that of stainless steel.

Heat pipes have been employed to achieve a load switching effect for thermal controls where a fixed amount of energy was transferred until the working fluid was transferred from one end of the pipe to the other [1.13].

The fourth type of switch is the gas gap heat switch, where the switching action depends on the presence or the absence of gas between two surfaces. Bywaters and Griffin [1.14] and later Nast, Bell, and Barnes [1.5] tested a gas gap heat switch which consisted of two concentric cylinders separated by a very thin gap. The gap was filled with helium gas to thermally couple the two cylinders, or evacuated to thermally isolate the cylinders. They used a gas bottle for the gas supply and a mechanical pump for gas evacuation. In the space environment, gas can be supplied from a gas bottle, turning the switch on, while evacuation is accomplished by opening valves to the vacuum in space, turning the switch off. This open system involves valves and requires active control. For repeated operation and reliability, it is more advantageous to use a sealed heat switch where the gas supply and the evacuation are provided by an adsorption [1.3, 1.7] [1.15 to 1.19] or an absorption pump connected to the switch. This technique has been previously proposed [1.16] and has been used in Rose-Innes and Rowland's liquid helium cryostat to release or pump away helium exchange gas, so as to establish and break thermal contact between two components [1.15]. However, they did not report any experimental data on their heat switch performance. Torre and Chanin [1.18] utilized liquid helium conductance for heat switching below lambda point. Tward [1.17] made a miniature heat switch which had a switch ratio of about 80 at 20 K. A better switch ratio of about 1000 at 4 K was recently reported [1.19].

Among the various physical mechanisms mentioned above, mechanically actuated heat switches have problems of performance reliability. Magnetoresistive heat switches are applicable at very low temperatures. Commandable heat switches operated by the heat pipe principle require low temperature valves and an active control system. Although in the past the closed system of the gas gap heat switch which was operated by an adsorption pump was ineffective, the concept has the following potentials:

(1) It is a simple sealed system and does not involve any moving parts. The adsorption and desorption are reversible processes and the system should be reliable for repeated operations over a long period of time.

(2) It is heat powered and its operation can be remotely controlled by ground command.

(3) The switch can be designed to be lightweight, miniaturized, and highly conductive, and has a high heat switch ratio.

(4) The switch can be designed to be self-actuated without any external power. The response time to the command of any operational switching change can be incorporated into the design.

Based on this observation, the concept of the sealed gas gap heat switch was chosen for the present study [1.2].

1.3 Present Study: Objective and Approach

The present study involves research and development of a heat switching system that can make and break thermal contacts for redundant parallel cryocoolers at three different cryogenic temperature levels (Fig. 1.1). The primary objective of the program is to demonstrate through design, analyses, and hardware that reliable heat switching can be achieved in space to meet the system requirements. A flow chart of the program activities is shown in Fig. 1.2. The first phase of the program started on March 10, 1985 and covered the previous 24 months. It was divided into three subprograms: hardware development, predictive methodology development, and system interface. The hardware development program was further divided into three phases: design, fabrication, and test. During the design phase, conceptual designs of heat switch components and test facilities were developed to meet the switching requirements. Special attention was given to the following parameters:

(1) the heat transfer area,
(2) the volume of the heat switch system,
(3) the weight of the heat switch system,
(4) the switch ratio of the ON and OFF conductance,
(5) the power required for the adsorption or absorption pump,
(6) the probability of system failure, and
(7) the vibration resistance of the system.

Following this six-month design phase, a design based on analyses and engineering judgment was chosen for the hardware fabrication, and the test setup was fabricated during the second half of 1985. Extensive tests of the heat switches and associated components were performed during 1986, with data reduction and report writing occurring in the last three months of 1986.
In parallel to the hardware development, the program had two major supportive tasks:

(1) Development of Predictive Methodology.

    This task developed methodology for the design and prediction of heat switch performance. This predictive methodology was used for data comparison.

(2) Development of Interface Criteria.

    The interfacing of the heat switches with other systems which include the refrigeration system and the optical system was examined. This task also involved contacts between JPL and cryocooler manufacturers.

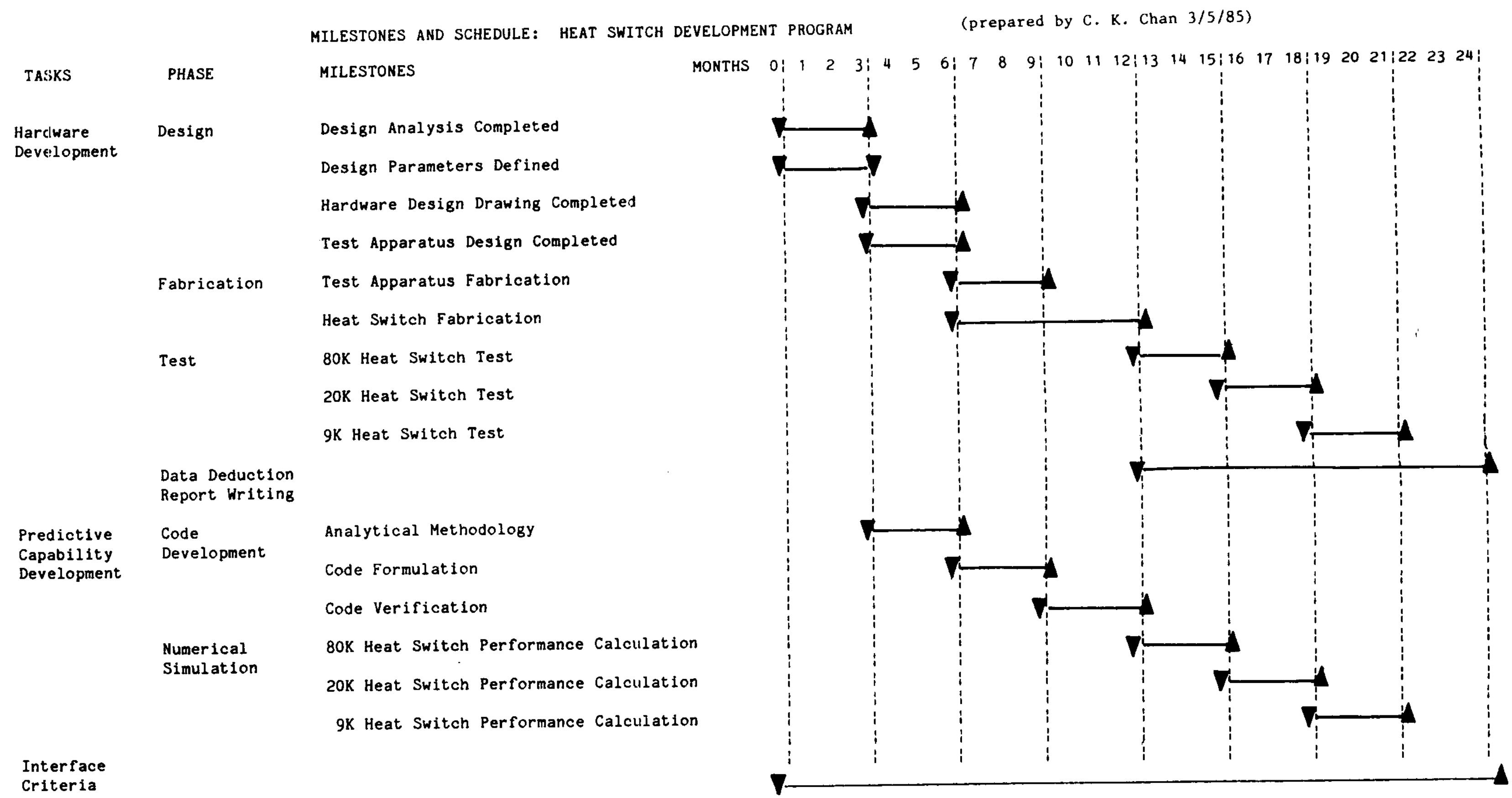

Figure 1.2. Flow Chart of the Heat Switch Development Program at JPL

This publication summarizes the results of the development effort. The publication is divided into nine sections. Following this introductory section (Section 1.0), the principle of operation, the various design concepts, and the design analyses of the heat switch system are presented in Section 2.0. Details of the mechanical drawings for the design and experimental apparatus are presented in Section 3.0, while the test procedures and results are presented in Section 4.0. An in-depth analytical model, which took into account various interacting heat transfer mechanisms, was developed to predict the heat switch performance (Section 5.0). The comparison of the test data with the predictive model, as well as the design model, is presented in Section 6.0. The interfacing of the heat switch with the optical and the refrigerator systems is analyzed in Section 7.0, which is followed by the conclusions, Section 8.0. References are listed in Section 9.0. The publication has four appendices, which outline the computer codes and sample runs that were developed under this program.

2.0 HEAT SWITCH DESIGN

A schematic of a gas gap heat switch operated by a small gas adsorption pump is shown in Fig. 2.1. Two high conductivity plates of area A are separated by a small gap d and held apart by a low conductivity support. The gas gap is connected via a tube having a small bore to a small adsorption pump which acts as a source and sink for the gas. The ON and OFF of the switches are operated by heating and cooling the adsorber pump, which then releases or readsorbs the gas, respectively. By means of a low conductance thermal link, the pump is cooled to the heat sink temperature, at which the gas is adsorbed, creating a high vacuum. When the adsorber is heated up by an electrical heater or by raising the heat sink temperature, the gas is released to the gas gap where the thermal conductance increases.

The thermal conductance between the two surfaces at the heat switch (Fig. 2.1), depends on the gas pressure caused by gas adsorption pump. Section 2.1 details the physics of gas conductance as functions of the gap size d, the type of the gas, and the gas pressure P. This principle of operation is then applied to the design of the heat switch which has extended surfaces or fins to increase the heat transfer area. The design of the heat switch and the gas adsorption pump, presented in Section 2.2, may proceed separately so long as they are compatible with each other in terms of gas volume, gas pressure, and gas type. Thermal resistance and networks are used in the design analyses, so a wide spectrum of design parameters such as the geometry and material of the fins and of the support at a wide range of temperatures can be encompassed. Based on these design analyses, a design is selected for fabrication and experimental tests.

2.1 Principle of Operation

When the gap is filled with gas, heat transfer between the surfaces is by gas conductance and thermal radiation. Heat transfer due to gas conduction depends upon gas conductivity which is a strong function of the gas temperature between the surfaces. At high pressures where the mean free path ℓ is much less than the gap width d, the gas is in the continuum state. The thermal conductivity of the gas is essentially independent of pressure and varies almost linearly with temperature. At low pressures is greater than d, the gas is in the free molecular flow state, and the gas conductivity is a function of both the temperature and the pressure. Between the continuum and the free molecular flow states is the transition state. A measure of these different heat conduction states is given by the Knudsen number (Kn) which is the ratio of ℓ over d, i.e.,

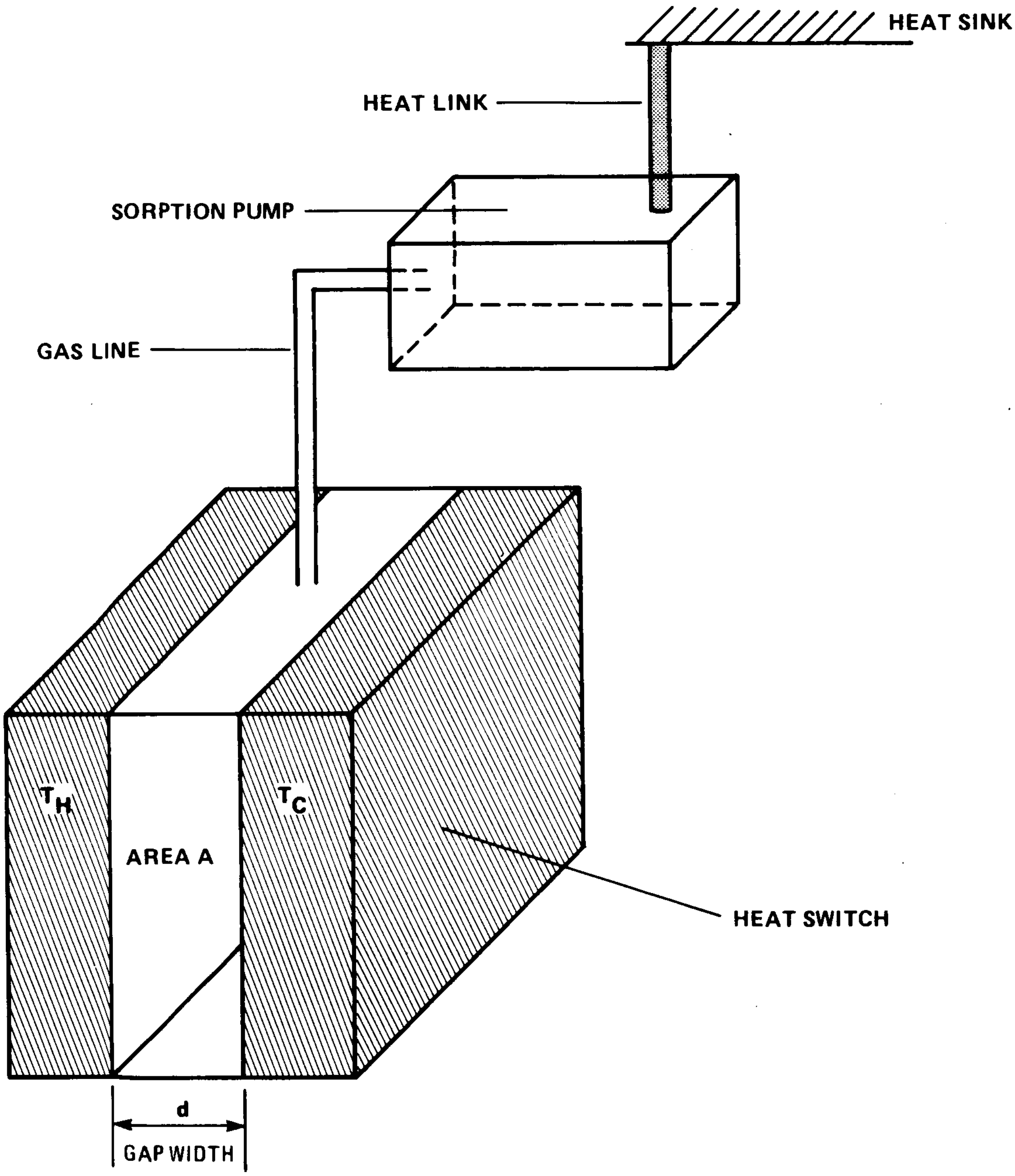

Figure 2.1. Gas Gap Heat Switch Operated by a Gas Adsorption Pump

$$Kn = \ell/d \tag{2.1.1}$$

where

d = gap width, cm
ℓ = mean free path, cm

The regimes of the thermal conductivities are given by [2.1]

$$\begin{array}{ll} \text{continuum} & Kn < 0.01 \\ \text{transition} & 0.01 \leq Kn \leq 1.0 \\ \text{free molecular flow} & Kn > 1.0 \end{array} \tag{2.1.2}$$

The mean free path ℓ in cm is a function of the gas pressure, temperature, viscosity, and molecular weight [2.1] as

$$\ell = 8.6(\mu/P)\sqrt{(T/M)} \tag{2.1.3}$$

where

8.6 = a numerical constant that accounts for unit conversions
μ = viscosity, poises
P = gas pressure, torr
T = gas temperature, K
M = molecular weight, gm/gm·mole

Substituting equation (2.1.3) for ℓ and equation (2.1.1) for Kn in equation (2.1.2), the different regimes for the gas conductance can be expressed in terms of the gas pressure and the gap width as:

$$\begin{array}{ll} \text{continuum} & P > 100\ \beta_1/d \\ \text{transition} & \beta_1/d \leq P \leq 100\ \beta_1/d \\ \text{free molecular flow} & P < \beta_1/d \end{array} \tag{2.1.4}$$

where

$$\beta_1 = 8.6\mu\sqrt{(T/M)} \tag{2.1.5}$$

The values of β_1 for three different gases (including nitrogen, hydrogen, and helium) at five different temperatures from 300 K to 4 K are presented in Table 2.1. For a given gas at a specified temperature, the limiting pressures given by equation (2.1.4) become:

$$P = 100\ \beta_1/d \tag{2.1.6a}$$
$$P = \beta_1/d \tag{2.1.6b}$$

These equations can be graphically plotted as two sets of lines as shown in Fig. 2.2 for nitrogen, hydrogen, and helium at five temperature increments ranging from 4 K to 200 K.

Table 2.1 Values of β_i(Torr–cm) as Functions of Temperatures and Gases

Temperature	4K	10K	20K	77K	300K
Nitrogen	--	--	--	0.00087	0.0051
Hydrogen	--	--	0.0003	0.0018	0.0095
Helium	0.00011	0.0003	0.00067	0.0032	0.015

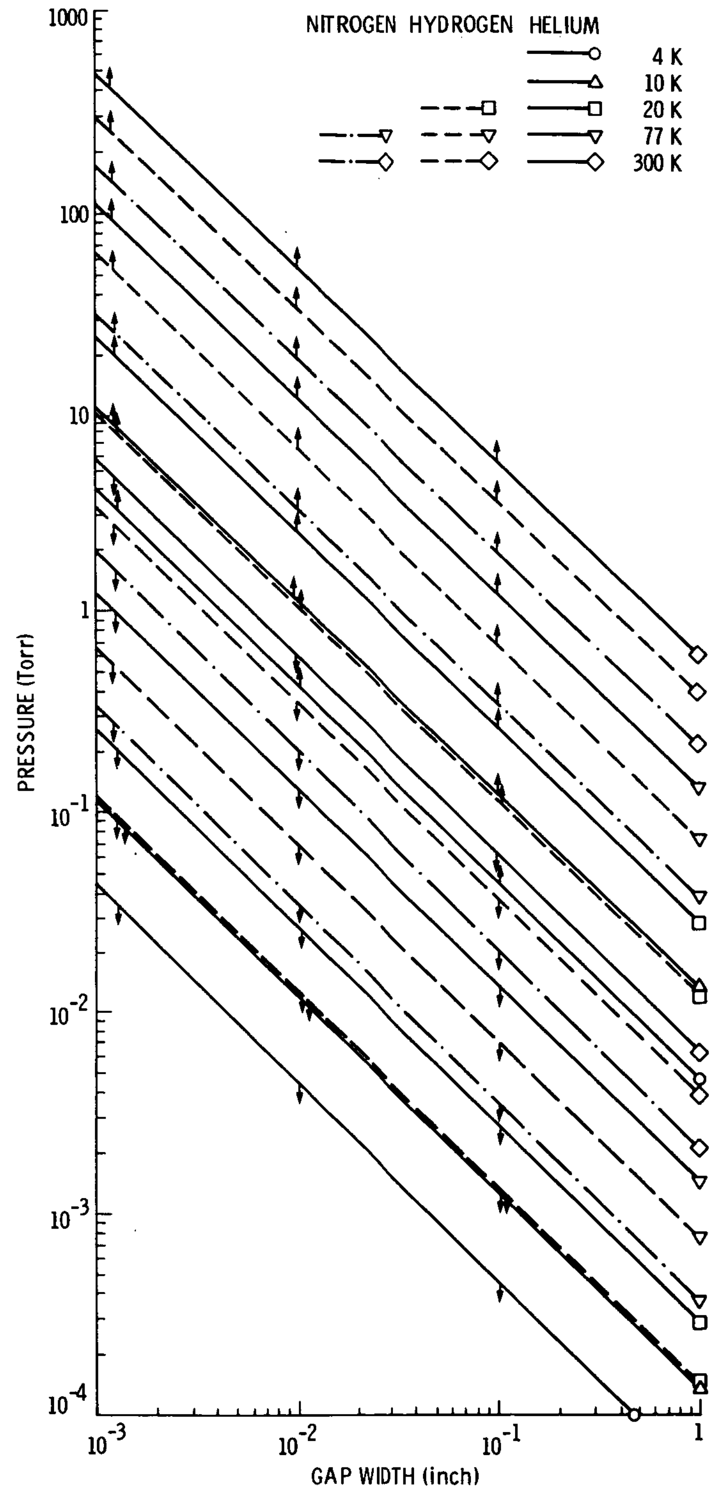

Figure 2.2. Regimes of Gas Conductance as Functions of Pressure, Gap Width, Temperature, and Gas

For the pressures below the line with the arrows pointing downward, the gas is in the free molecular regime. For pressures above the line with the arrows pointing upward, equation (2.1.6a), the gas is in the continuum state. Between these lines is the transition state. The limiting lines are extremely useful if one would like to know the minimum pressure swing in the heat switch for a given gap size. For example, due to fabrication limitations, the gap size is two thousandths of an inch. If the switch action is taking place in the 20 K range, then the pressure swing from the continuum state to the free molecular flow state is from 6 torr to 0.07 torr for hydrogen gas and from 10 torr to 0.1 torr for helium gas.

In the free molecular flow regime, the gas conductivity is proportional to the gas pressure as [2.1]

$$k_{fm}/d = \sqrt{(R/8\pi MT)} \quad [(\gamma + 1)/(\gamma - 1)] \ (\alpha P) \qquad (2.1.7)$$

where

k_{fm}	=	gas conductivity in the free molecular regime, W/cmK
d	=	gap width, cm
R	=	gas constant, $\sqrt{R/8\pi}$ has the value 0.2426 for k_{fm}, W/cmK
γ	=	specific heat ratio Cp/C_v of the gas
M	=	molecular weight of the gas, gm/gm·mole
T	=	gas temperature, K
P	=	gas pressure, torr
α	=	overall accommodation coefficient for the areas of the surfaces A_1 and A_2; $\alpha_1\alpha_2/[\alpha_2 + \alpha_1(1 - \alpha_2)A_1/A_2]$ (2.1.7a)

where α_1 and α_2 are accommodation coefficients for surfaces A_1 and A_2, respectively.

Hence, for effective thermal isolation when the switch is OFF, the pressure should be as low as possible and lower than those given by the limiting lines illustrated in Fig. 2.2.

For helium gas when M = 4.003 and γ = 1.67, equation (2.1.7) is reduced to

$$k_{fm}/d = 0.4826 \ (\alpha P)/\sqrt{(T)} \qquad (2.1.8)$$

As α is a function of the temperature [2.1] as shown in Table 2.2, for a given temperature k_{fm} is a linear function of P.

When

T	=	10 K	20 K	80 K	
k_{fm}/d	=	0.0715P	0.0463P	0.0135P	(2.1.9)

The plots of k_{fm}/d versus P for these three temperatures are the three sloping lines in Fig. 2.3. The gas conductance increases with pressure until it reaches the continuum regime where the conductance is no longer a function of the pressure. For monatomic gas, it is given by equation (8.3.13) of Ref. [2.2] as

$$k_g = 8.314\times10^{-10} \sqrt{(T/M)/(\sigma_L \Omega_k)} \qquad (2.1.10)$$

where

k_g = gas conductivity, W/cm K
T = temperature, K
M = molecular weight, gm/gm·mole
σ_L = Lenard-Jones Parameter (A) (Table B-1 of Ref. [2.2])
Ω_k = collision function Table B-2 of Ref. [2.2]

For helium gas where $M = 4.003$ and $\sigma_L = 2.576$A

$$k_g = 6.27\times10^{-5} \sqrt{T}/\Omega_k \qquad (2.1.11)$$

For	T	=	10 K	20 K	80 K	
	Ω_k	=	1.6038	1.183	0.8568	(2.1.12)
and	k_g(W/cmK)	=	1.24×10^{-4}	2.37×10^{-4}	6.54×10^{-4}	(2.1.13)

For a gap of 0.002 in. (0.0051 cm)

$$K_g \doteq k_g/d \ (W/cm^2K) = 2.43\times10^{-2} \quad 4.66\times10^{-2} \quad 1.28\times10^{-1} \qquad (2.1.14)$$

Values of k_g as functions of temperatures for different gases are shown in Fig. 2.4.

The conductances given by equation (2.1.14) are represented by the three lines in Fig. 2.3. The transition regime between the continuum and the free molecular regimes is neglected here because the conductance in the transition regime is very close to the values given by equation (2.1.7). From Fig. 2.3 it is therefore apparent that at some fixed operating temperature the thermal conductance between two surfaces may be varied from some high fixed value in the continuum regime to some lower value which is pressure dependent. In a real switch, however, the

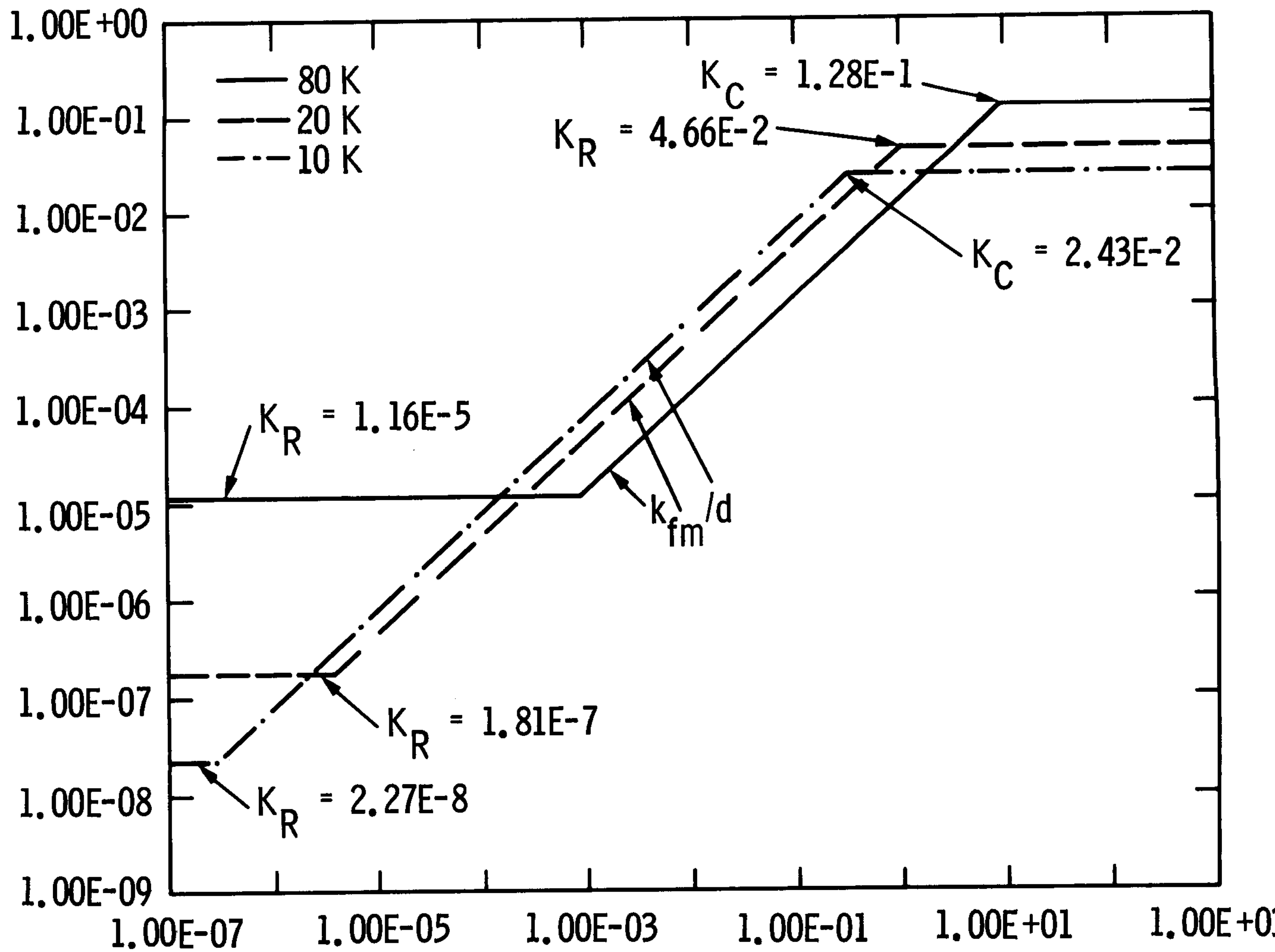

Figure 2.3. Thermal Conductance of Helium Gas as a Function of Pressure and Temperature

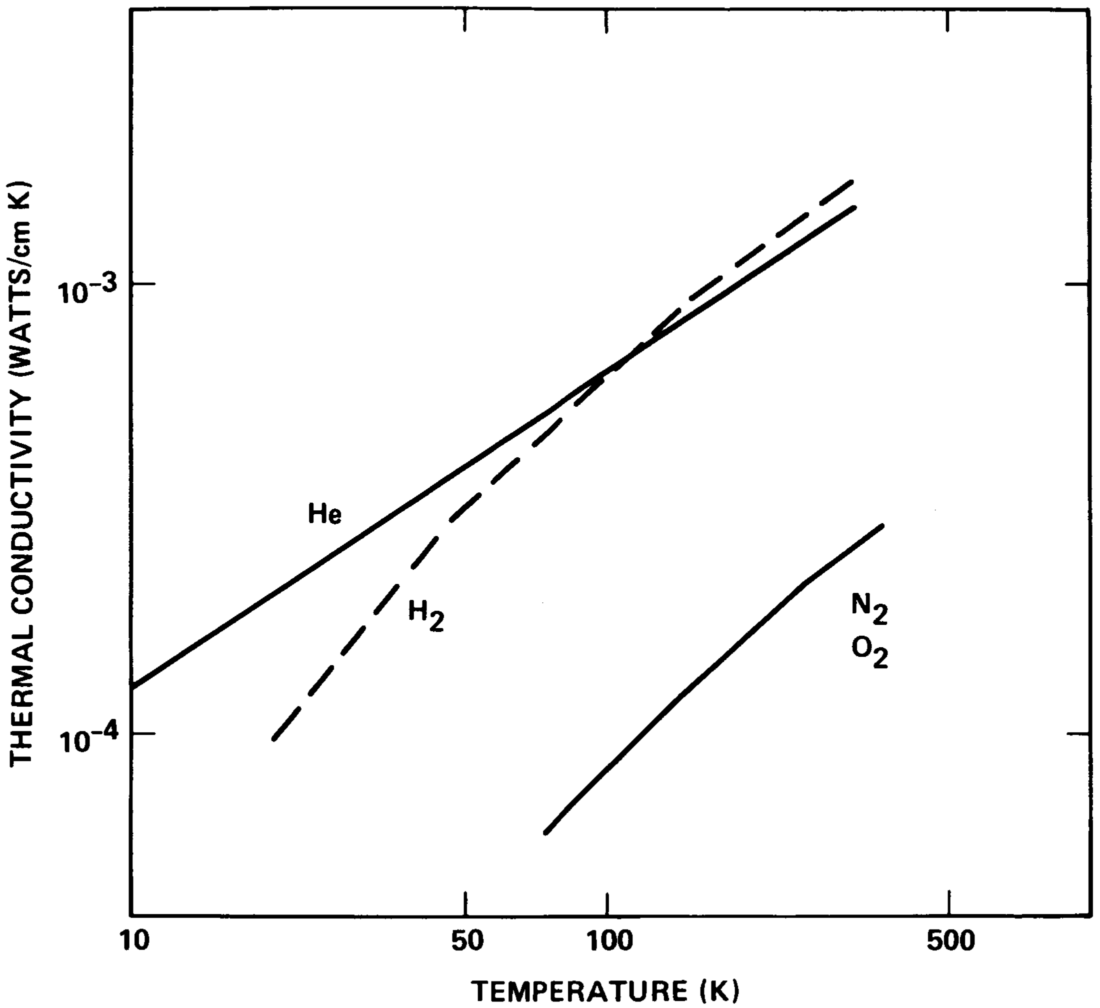

Figure 2.4. Thermal Conductivities of Different Gases in Continuum Regime as Function of Temperatures

minimum conductance is determined by other thermal conductances operating in parallel to the conductance through the gas. These conductances arise due to the heat transfer by radiation between the two surfaces, and due to the heat transfer by conductance through the supporting structure holding the two surfaces apart.

The radiative heat flow q_R between the two parallel surfaces at temperatures T_1 and T_2 is

$$q_R = \bar{\epsilon}\sigma_S(T_1^4 - T_2^4) \qquad (2.1.15)$$

where

$$\bar{\epsilon} = 1/(1/\epsilon_1 + 1/\epsilon_2 - 1) \qquad (2.1.16)$$

ϵ_1, ϵ_2 = emissivities of surfaces 1 and 2

σ_S = Stefan-Boltzmann Constant, $5.6697\text{x}10^{-12}$ W/cm^2K^4

If T_1 is close to T_2, the effective thermal conductance due to the radiation can be approximated as [2.3]

$$K_R = 4\bar{\epsilon}\sigma_S T^3_{av} \qquad (2.1.17)$$

where

$$T_{av} = (T_1 + T_2)/2.0$$

For black surfaces $\epsilon_1 = \epsilon_2 = 1$, when

T_{av} =	10 K	20K	80K	
$K_R(W/cm^2K)$ =	$2.27\text{x}10^{-8}$	$1.81\text{x}10^{-7}$	$1.61\text{x}10^{-5}$	(2.1.18)

These values of K_R are plotted in Fig. 2.3 for comparison. However, since K_R is linearly proportional to ϵ, the radiation contribution can be cut down by using a highly reflective surface, such as polished gold, which has a surface emissivity of 0.02. Hence, for the polished gold surfaces, when

T_{av} =	10 K	20 K	80 K	
$K_R(W/cm^2K)$ =	$2.27\text{x}10^{-10}$	$1.81\text{x}10^{-9}$	$1.61\text{x}10^{-7}$	(2.1.19)

These values are two orders of magnitude lower than those for the black surfaces.

Thus, for a given gas, irrespective of the design, the maximum switch ratio would be the maximum conductance K_g, over the minimum value. If the pressure is low enough so the radiation is greater than the free molecular conductance, the switch ratio (S.R.) is given by

$$S.R. = K_g/K_R \qquad (2.1.20)$$

where K_g and K_R are given by equations (2.1.14) and (2.1.17), respectively. For

T	=	10 K	20 K	80 K	300 K	
S.R.	=	$5462/(\bar{\epsilon}d)$	$1309/(\bar{\epsilon}d)$	$56/(\bar{\epsilon}d)$	$1.6/(\bar{\epsilon}d)$	(2.1.20)

However, at low temperatures, the free molecular conductance may be the limiting factor and the switch ratio S.R. is given by

$$S.R. = K_g d/k_{fm} \qquad (2.1.21)$$

where K_g and k_{fm} are given by equations (2.1.14) and (2.1.9). For

T	=	10 K	20 K	80 K	
S.R.	=	$8.1\times10^{-4}/(Pd)$	$5.1\times10^{-3}/(Pd)$	$4.8\times10^{-2}/(Pd)$	(2.1.21)

The lesser value of the switch ratio given by equations (2.1.20) and (2.1.21) would be the maximum switch ratio for any given gap size, pump pressure, and surface emissivity. This technique can be used as a simple calculation to determine whether the gas gap heat switch will meet the system requirements.

2.2 Heat Switch Design and Analyses

The heat switch for the present application as outlined in Section 1.1 has to accommodate the transfer of a large quantity of heat over a small temperature difference between the cold plate and the cold finger. Since the heat flow between two surfaces is directly proportional to the heat transfer area and inversely proportional to the distance between the surfaces, the gas gap width d has to be small and the surface area A has to be large. In order to meet these stringent requirements, the hot side and the cold side of the heat switch would be two pieces of high-conductivity material, each of which would have an array of extended heat transfer surfaces or fins (Fig. 2.5). The fin pattern on each piece is a mirror image of the other, and the width of each groove is twice the desired gap width d plus the fin width, so when the two pieces are put together there is a gap of d between the fins. These two pieces are held together by

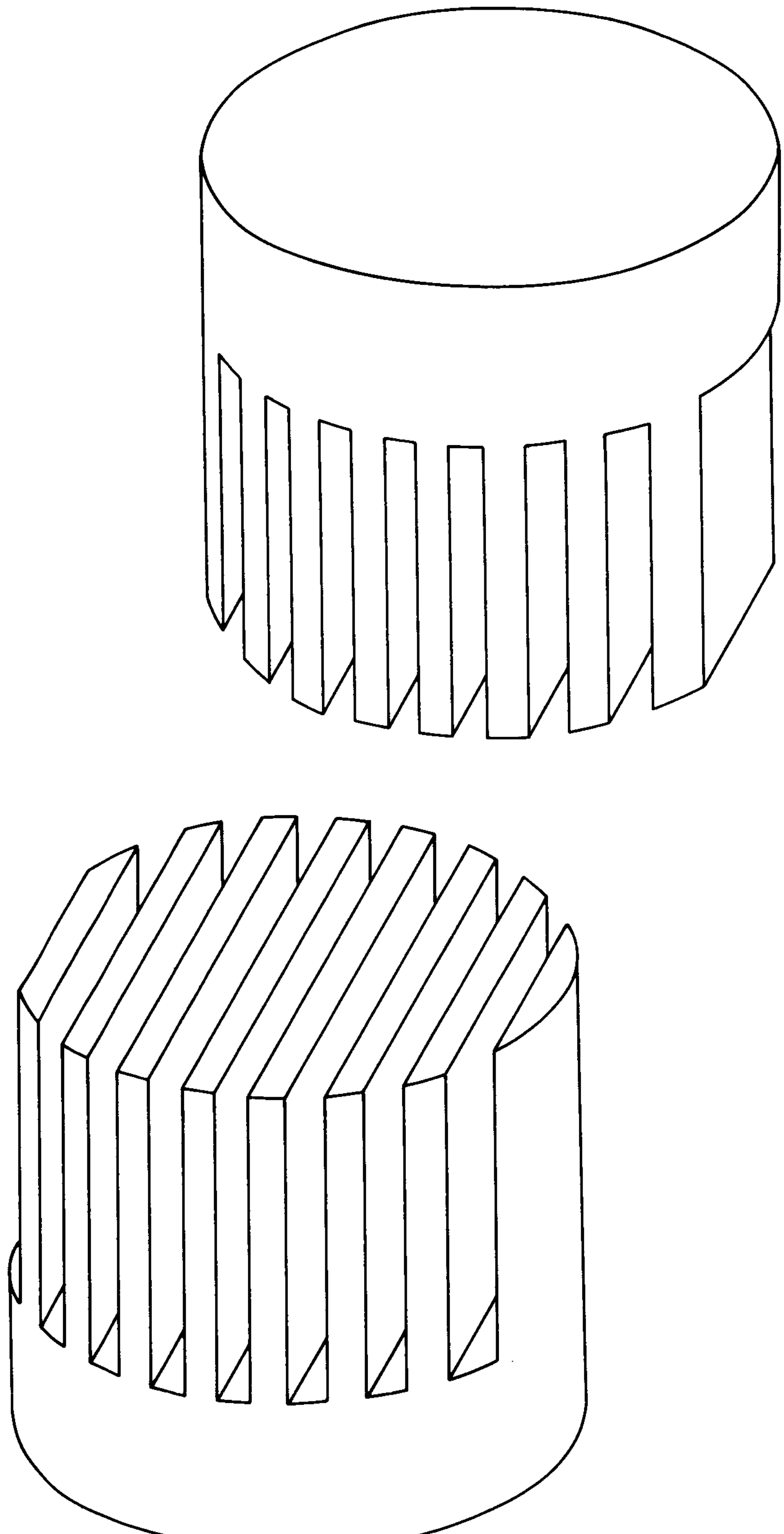

Figure 2.5. Extended Straight Fins on Metal Base

a supporting tube of low conductance which also provides a sealed gas envelope for the heat switch. There are gaps at the top and bottom of the fins, so there is no surface contact between the two pieces (Figs. 2.6 and 2.7).

There are numerous ways to arrange a fin pattern on a metal base. There are rectangular fins protruding from a circular base (Figs. 2.5 to 2.7). There are pie-shaped fins cut out from a solid cylinder (Figs. 2.8 and 2.9). The most effective way to accommodate a large heat transfer area in a small volume would be a waffle pattern (Fig. 2.10). However, the difficulty in assembling the switch's gap in thousandths of a inch for this waffle pattern discourages us from pursuing this design at present.

Analysis of the various designs of the heat switch and the adsorption pump is divided into two parts (Fig. 2.11). The heat switch design subroutine would read the inputs of: (a) the temperature requirements at which the switch will operate, (b) the geometry and the material choice of the fins, (c) the emissivity of the coating material on the fins, (d) the geometry and the material choice of the support tube, (e) the gas pressure from the gas adsorption pump during the on mode and the off mode, and (f) the type of gas.

The last two items are also the interacting parameters between the heat-switch design subroutine and the gas adsorption-pump design subroutine. The major outputs of the heat-switch design subroutine are the thermal conductance K when the heat switch is on and when it is off. These on and off conductances are comprised of three terms:

(1) the heat transfer through the solid fin and across the gas gap by gas conduction, to the other fin, to the fin base, and to the support tube,

(2) the heat transfer, by radiation across the gap mentioned in item (1), and

(3) the heat transfer through the support tube by conduction from the hot base to the cold base, and by gas conduction and radiation from the sides of the fins to the inside wall of the support tube.

Because of the complexity of these heat transfer mechanisms, several assumptions were made in the present analysis. The heat paths are assumed to be independent and parallel to each other. The on conductance is then given by

$$K_{ON} = K_C + K_R + K_L \qquad (2.2.1)$$

The off conductance is given by

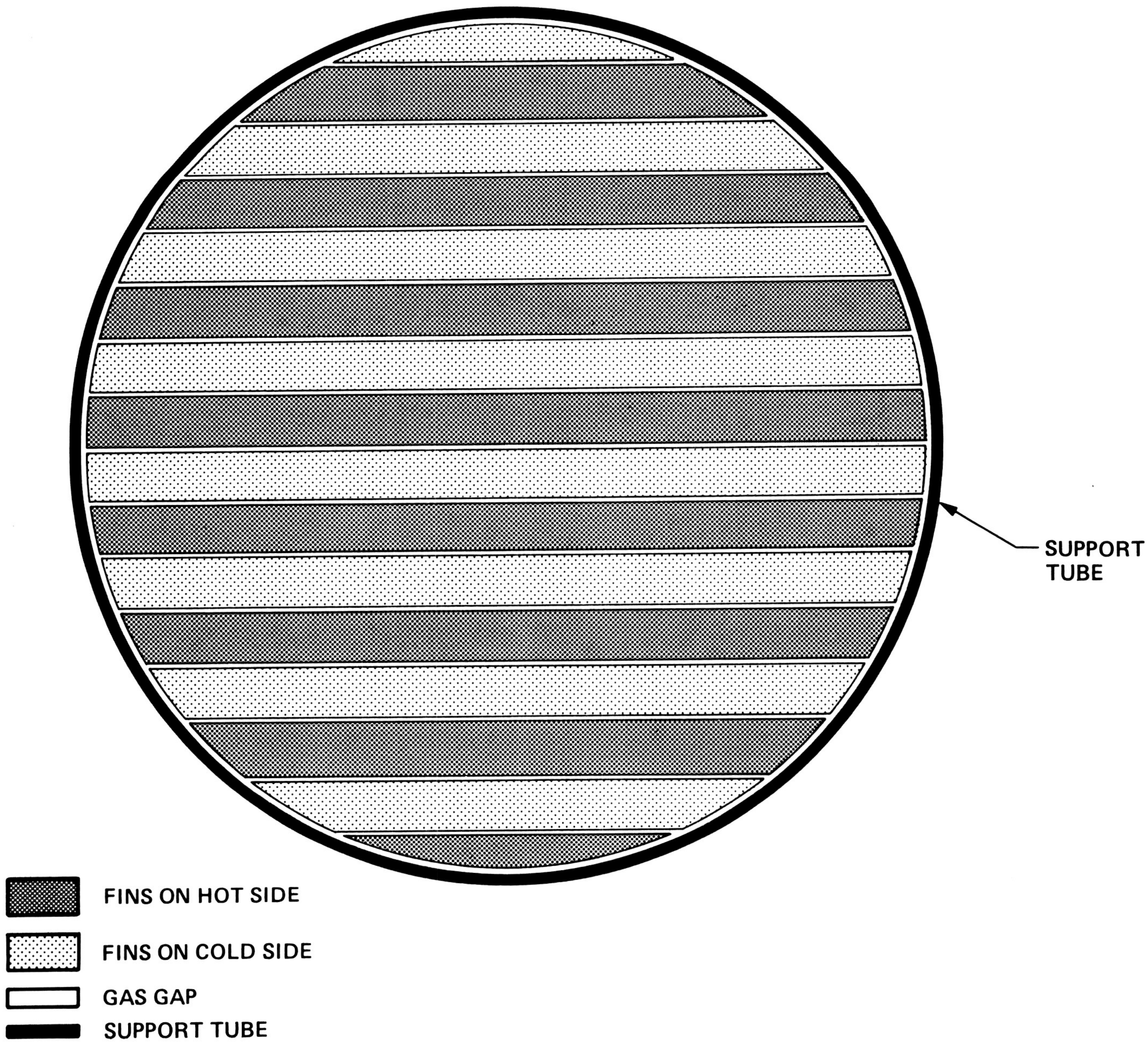

Figure 2.6. Cross-Sectional View of a Straight Fin Heat Switch

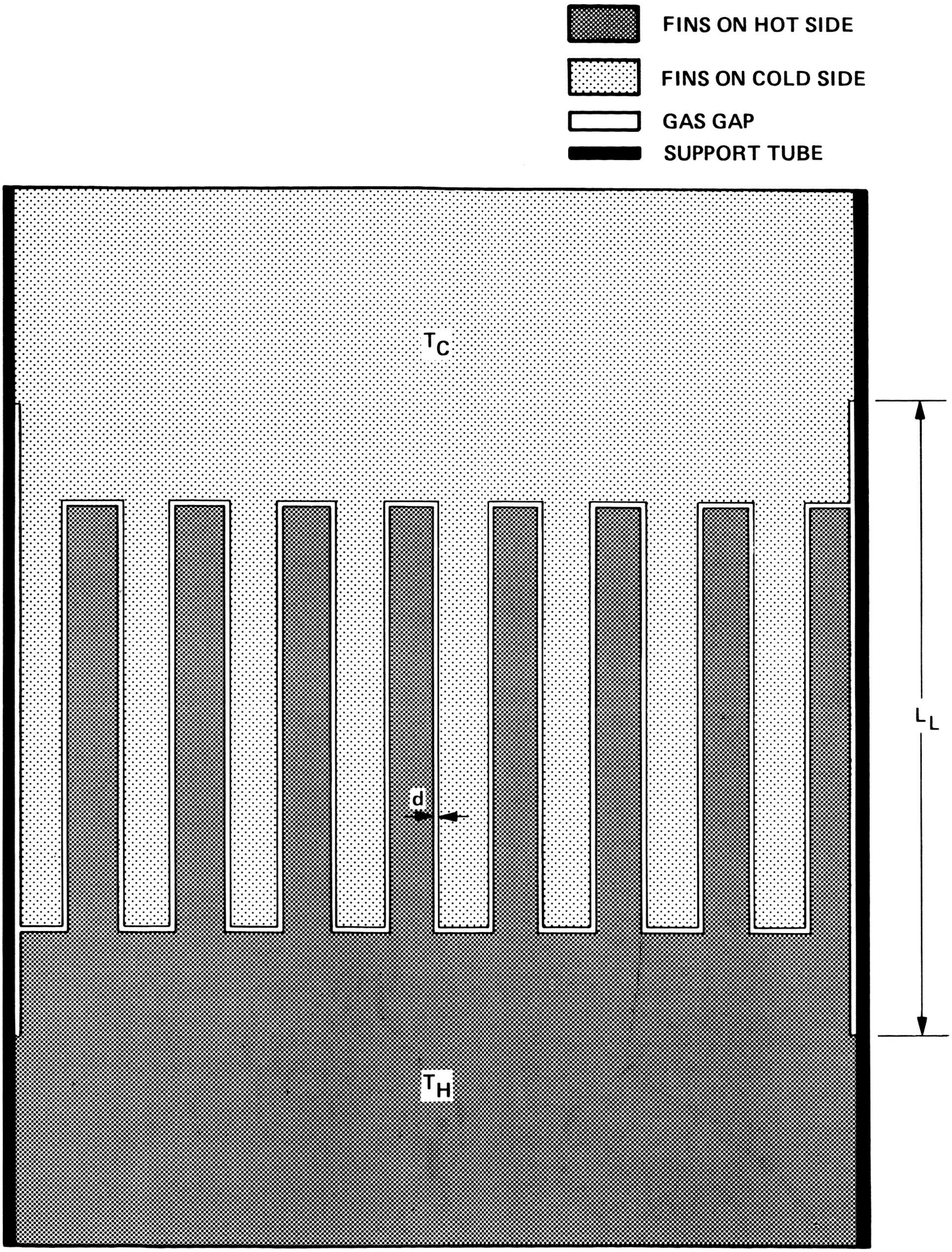

Figure 2.7. Front View of a Straight Fin Heat Switch

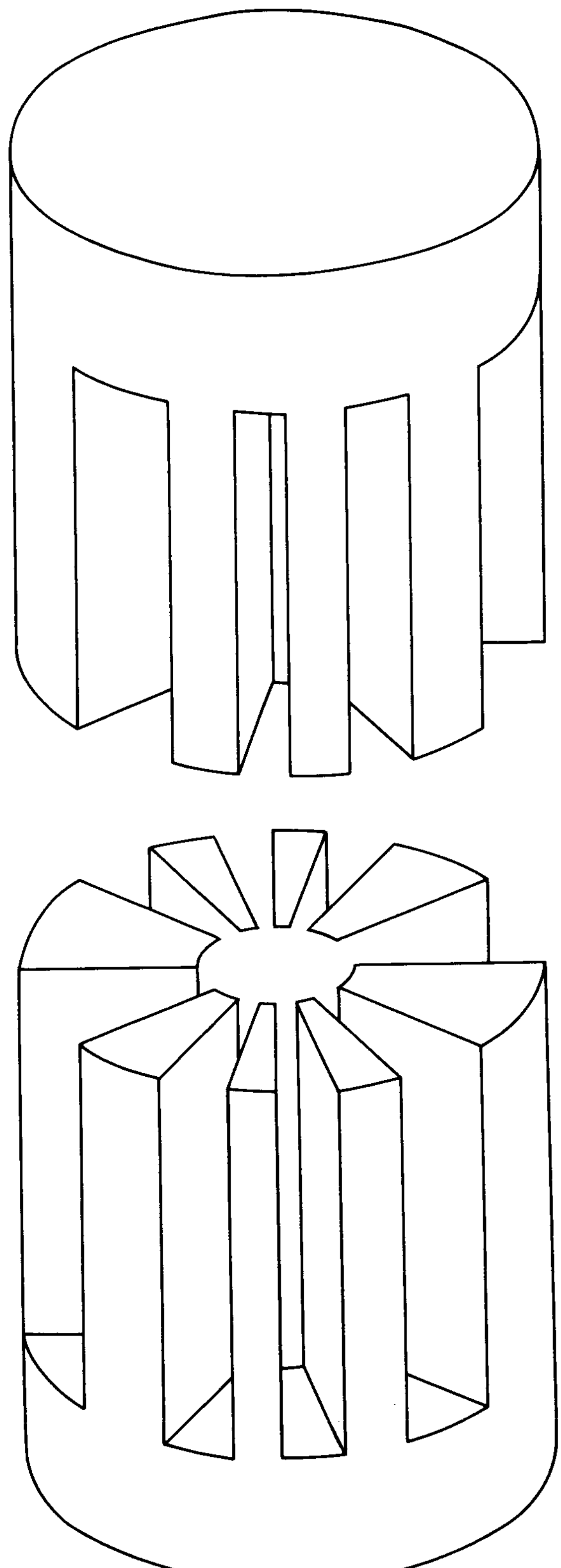

Figure 2.8. Extended Pie Shape Fins on Metal Base

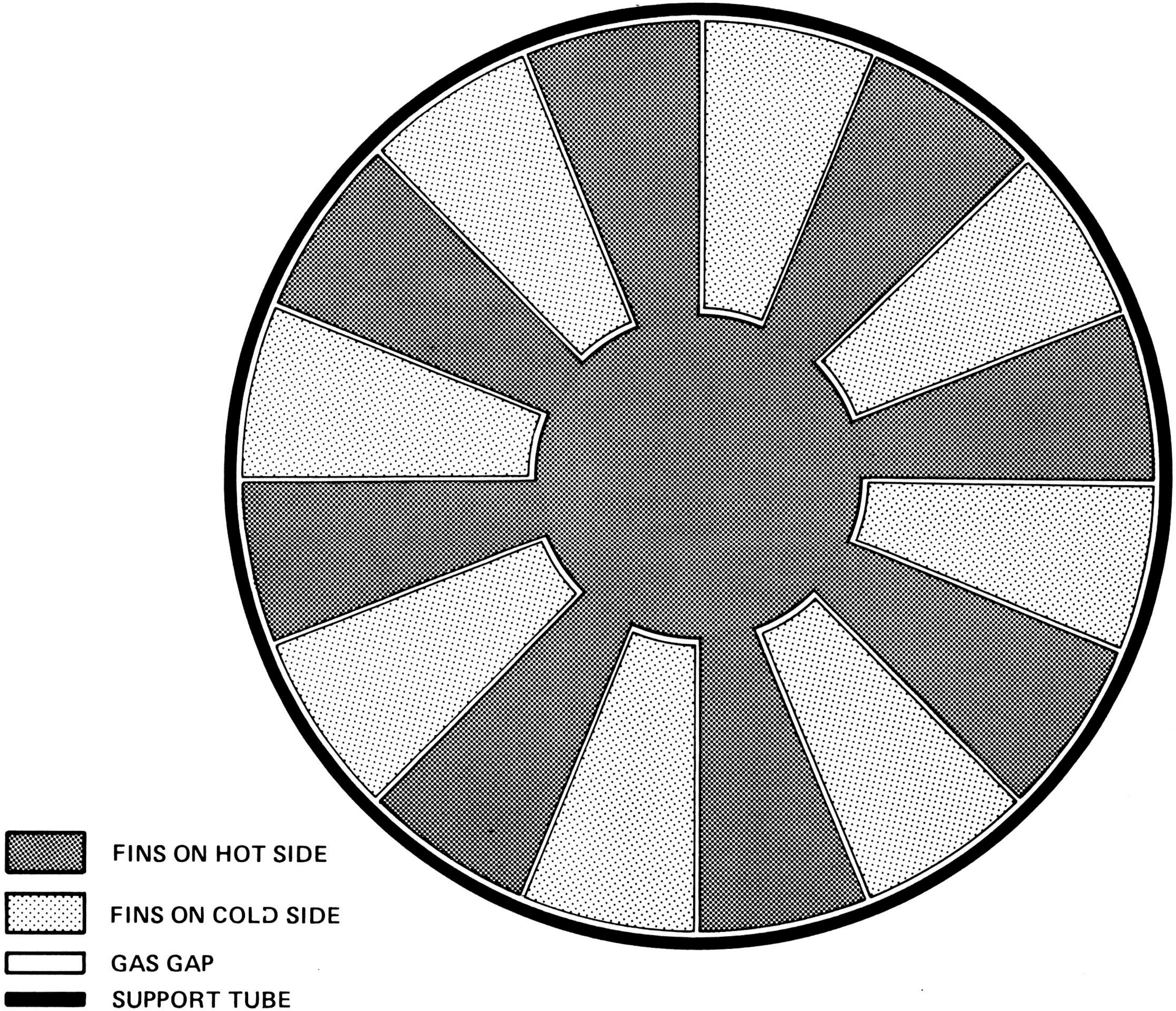

Figure 2.9. Cross-Sectional View of Pie-Fin Heat Switch

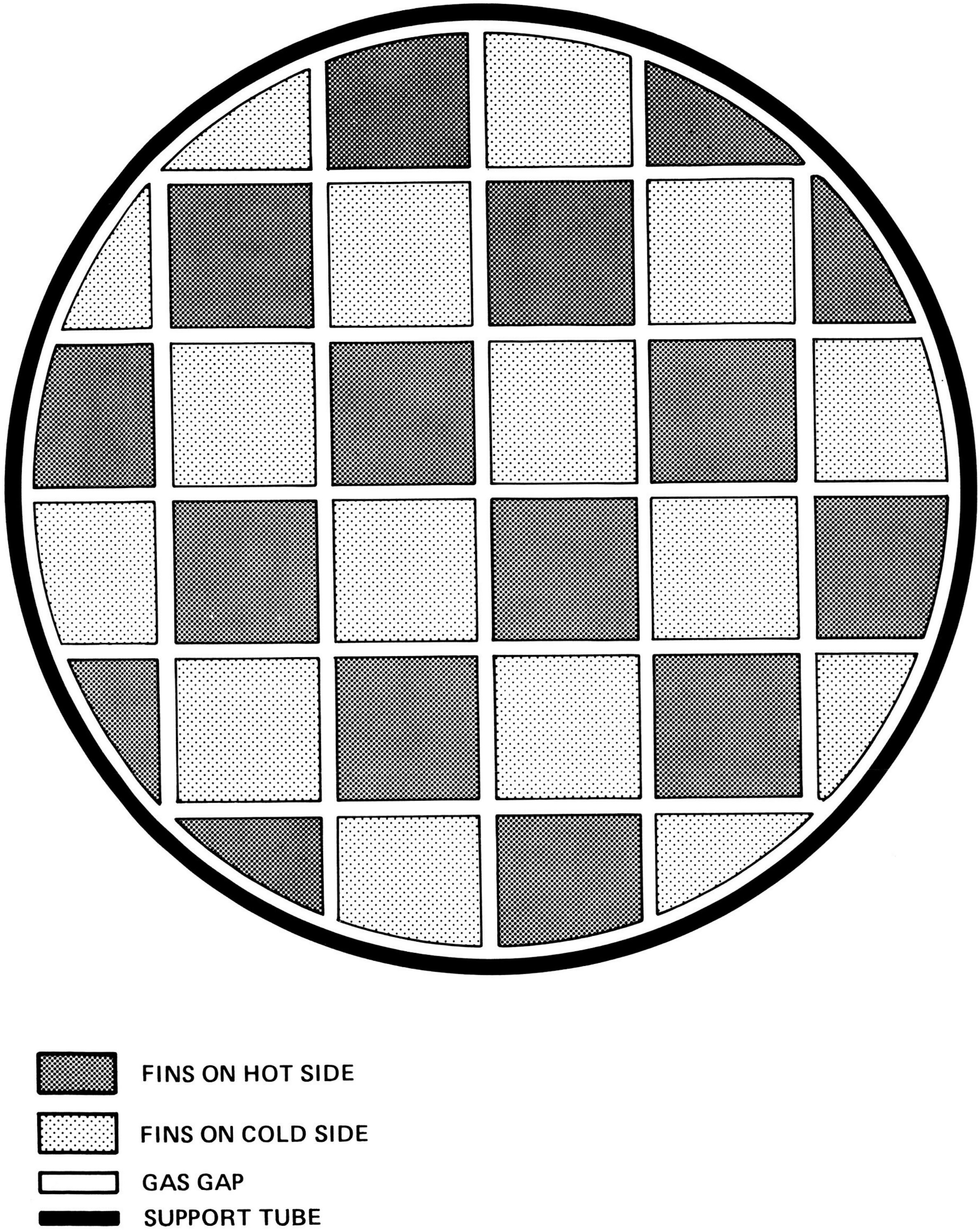

Figure 2.10. Cross-Sectional View of Waffle Pattern Heat Switch

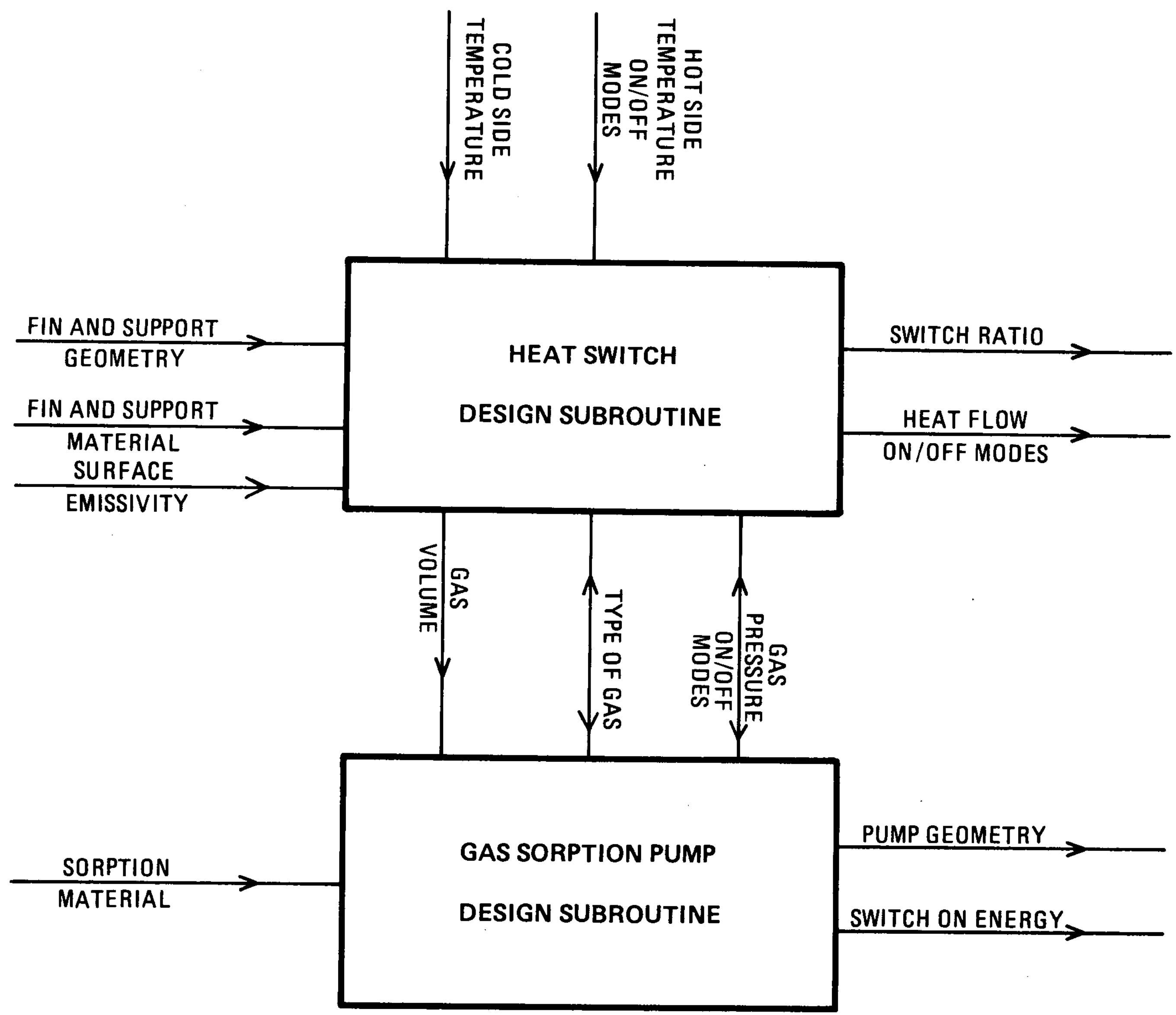

Figure 2.11. Gas Adsorption/Absorption Heat Switch Design Program

$$K_{OFF} = K_{fm} + K_R + K_L \qquad (2.2.2)$$

where

K_C = conductance when gas is in continuum regime, W/k
K_{fm} = conductance when gas is in free molecular flow regime, W/k
K_R = conductance due to radiation, W/k
K_L = conductance through the support, W/k

All units for K are W/K. Assuming the adiabatic boundary at the end of the fin tip, for each pair of fins numbered as shown in Fig. 2.12, the combined effect of fin conductivity and gas conductivity on K_C and K_{fm} can be expressed as [2.4]:

$$K_{C,i} = h_C \, pL \, G_C \qquad (2.2.3)$$

and

$$K_{fm,i} = h_{fm} \, pL \, G_{fm} \qquad (2.2.4)$$

where

h_C = $2k_g/d$, W/cm^2K (2.25)
k_g = gas conductivity in continuum regime, a function of temperature, W/cmK

d = gap width, cm

h_{fm} = $2\ k_{fm}/d$, W/cm^2K (2.2.6)

k_{fm} = gas conductivity when gas is in free molecular flow regime, a function of pressure and temperature as shown by equation (2.1.7), W/cmK

p = fin perimeter, cm

L = fin length, cm

G = Tanh (BL)/BL, dimensionless (2.2.7)

B^2 = $h_C p/k_m A_i$ or $h_{fm} p/k_m A_i$, cm^{-2} (2.2.8)

G_C, G_{fm} = depend on the value of h_C and h_{fm}, respectively

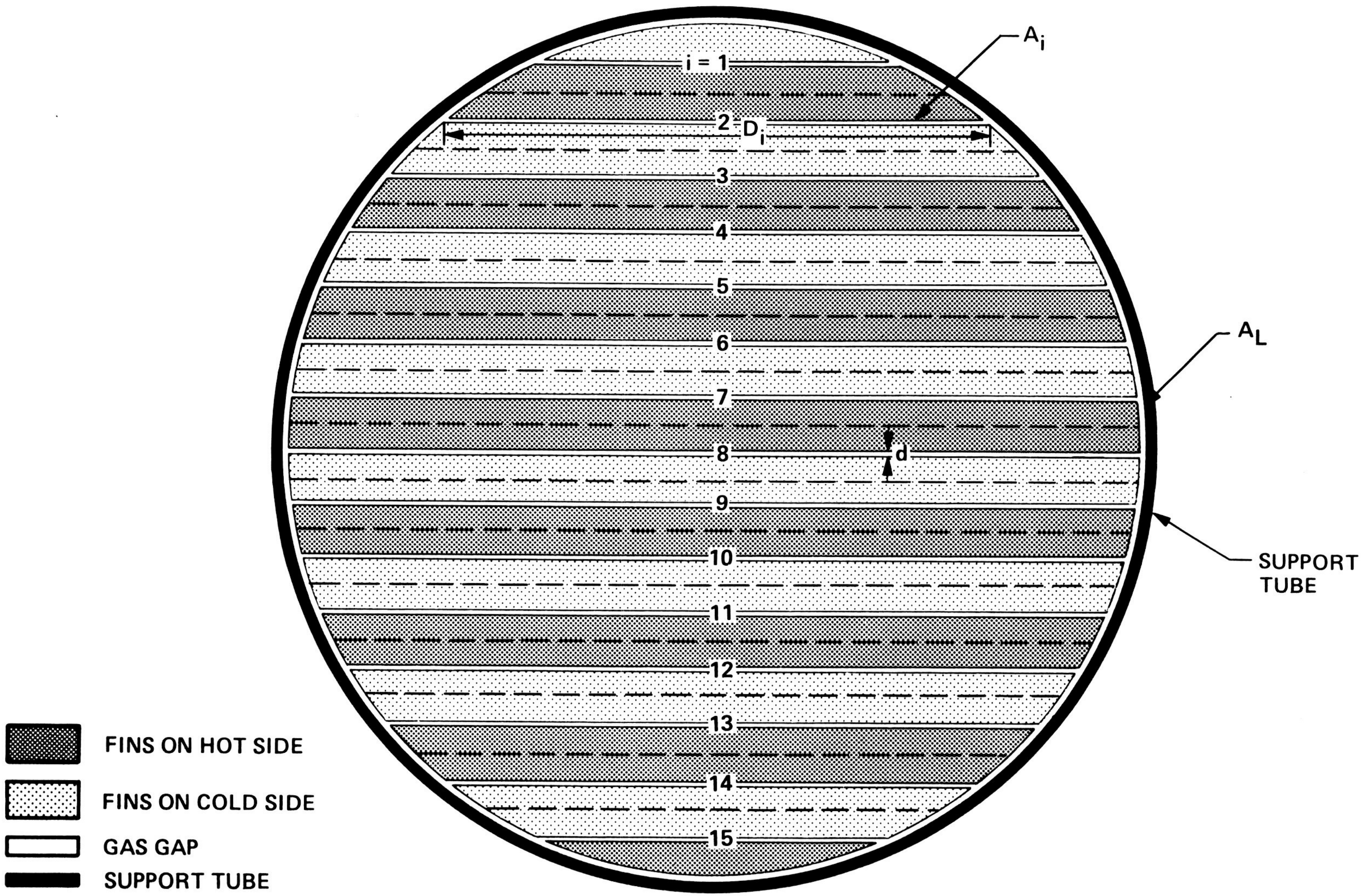

Figure 2.12. Control Volumes of Each Pair of the Straight Fins

k_m = material conductivity, a function of temperature, W/cmK

A_i = cross-section of the fin, cm^2

Then, for n pairs of fins or n gas gaps in the heat switch, the conductances K_C and K_{fm} are given by

$$K_C = \sum_{i=1}^{n} K_{C,i} \qquad (2.2.9)$$

$$K_{fm} = \sum_{i=1}^{n} K_{fm,i} \qquad (2.2.10)$$

The radiative conductance K_R is given by

$$K_R = \bar{\epsilon}\sigma_s A_f (T_H + T_C)(T_H^2 + T_C^2) \qquad (2.2.11)$$

where

$$\bar{\epsilon} = (1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1} \qquad (2.2.12)$$

ϵ_1, ϵ_2 = surface emissivities of the hot and cold fins, respectively

T_H, T_C = temperatures of the hot and cold sides, respectively, K

σ_s = Stefan-Boltzmann Constant, W/cm^2K^4

A_f = total fin area, cm^2

If T_H and T_C are close together, equation (2.2.11) can be approximated as

$$K_R = 4\bar{\epsilon}\sigma_s A_f T_{av}^3 \qquad (2.2.13)$$

where

$$T_{av} = (T_H + T_C)/2.0 \qquad (2.2.14)$$

The conductance through the supporting tube is

$$K_L = k_L A_L / L_L \qquad (2.2.15)$$

where

L_L = tube length over the gap as shown in Fig. 2.7, cm
k_L = thermal conductivity of the tube material, W/cmK
A_L = tube cross section, cm^2

The heat flows due to these three different heat transfer mechanisms during the on mode are

$$Q_{ON,C} = K_C(T_H - T_C)_{ON} \quad (2.2.16)$$

$$Q_{ON,R} = K_R(T_H - T_C)_{ON} \quad (2.2.17)$$

$$Q_{ON,L} = K_L(T_H - T_C)_{ON} \quad (2.2.18)$$

while

$$Q_{ON} = Q_{ON,C} + Q_{ON,R} + Q_{ON,L} \quad (2.2.19)$$

During the off mode, the heat flows are

$$Q_{OFF,fm} = K_{fm}(T_H - T_C)_{OFF} \quad (2.2.20)$$

$$Q_{OFF,R} = K_R(T_H - T_C)_{OFF} \quad (2.2.21)$$

$$Q_{OFF,L} = K_L(T_H - T_C)_{OFF} \quad (2.2.22)$$

while

$$Q_{OFF} = Q_{OFF,fm} + Q_{OFF,R} + Q_{OFF,L} \quad (2.2.23)$$

The unit of Q is W.

An approximated method to include the heat transfer at the edges and end of the fins and inside the support tube would be a correction factor η which is multiplied to Q_{ON} and Q_{OFF} given by equations (2.2.19) and (2.2.23). This factor η takes into account the extra heat transfer area due to the edges and the ends of the fins, as well as the inside surface of the support tube. Based on the current design, the maximum value of η is estimated to be 1.3.

There can be two definitions of the heat switch ratio: one based on conductance and the other based on heat flows. The switch ratio based on conductance is

$$S.R. = K_{ON}/K_{OFF} \quad (2.2.24)$$

The switch ratio based on heat flows is

$$(S.R.)_Q = Q_{ON}/Q_{OFF} \quad (2.2.25)$$

The model in this section is an approximated approach where conduction and radiation are decoupled. The interaction between these two modes of heat transfer will be analysed in Section 5. The correction for the heat transfer at the edges should be handled by a more exact model using finite elements which will be developed in the second phase.

2.3 Design Trade-Off

Based on the above methodology, a computer program was written in Fortran 77 to compute the heat switch performance, using an IBM PC. All the temperature dependent properties, such as the gas thermal conductivities, the fin and the support material, as well as the surface emissivity, were incorporated in the program. There is no linearized approximation for the radiation term. The fin area computation was based on the fin pattern design. The listing of the program and an example of how to execute the program, including the inputs and outputs, is shown in Appendix A. Computer runs were performed for:

(1) two fin patterns: straight fins and pie fins,

(2) two different gases: hydrogen and helium,

(3) two different surface emissivities:
$\epsilon = 0.4$ for copper
$\epsilon = 0.02$ for gold plated copper,

(4) four different support tube materials and geometries:
a 40-mil thick glass tube,
a 40-mil thick G-10 tube with 0.5 mil stainless steel lining,
two stainless steel tubes (one 4-mil and the other 2 mil thick),

(5) three different temperature levels: 10 K, 20 K, and 80 K, and

(6) five different pressure levels from 10^{-3} to 10^{-7} torr.

The documentation of these runs is listed in Table 2.2. The physical dimensions which are constant for all the runs are:

(1) the fin base of the switch = 2 inches (5.08 cm) in diameter
(2) the fin length = 1 inch (2.54 cm)
(3) the fin width = 1/8 inch (0.3175 cm),
(4) the tube length L_L = 1.5 inches (3.81 cm), and
(5) the gas gap = 0.002 inch (0.00508 cm).

The on and the off conductances and the heat switch ratio for the 95 cases are shown in Table 2.3 and plotted as a function of gas pressure in Figs. 2.13 to 2.18. These results show that:

Table 2.2 Computer Run Cases

Straight Fin Design

Fin Material	Support Tube Material	Off Pressure (Torr)	He 8-9K Case #	He 20-22K Case #	He 80-85K Case #	H2 20-22K Case #	H2 80-85K Case #
Copper (TP)	CASE A						
$\epsilon = 0.4$	Glass	1E-3	1	1	1	1	1
	t=0.102	1E-4	2	2	2	2	2
	(cm)	1E-5	3	3	3	3	3
	CASE B						
	G-10	1E-3	1	1	1	1	1
	t=0.102	1E-4	2	2	2	2	2
	(cm)	1E-5	3	3	3	3	3
	CASE C						
	Steel	1E-3	1	1	1	1	1
	t=0.0102	1E-4	2	2	2	2	2
	(cm)	1E-5	3	3	3	3	3
		1E-6	4	4	4	4	4
		1E-7	5	5	5	5	5
Copper with	CASE D						
Polished	Steel	1E-4	2	2	2	2	2
Gold	t=0.0102	1E-5	3	3	3	3	3
Surface	(cm)	1E-6	4	4	4	4	4
$\epsilon = 0.02$		1E-7	5	5	5	5	5
	CASE E						
	Steel	1E-4	2	2	2	2	2
	t=0.0051	1E-5	3	3	3	3	3
	(cm)	1E-6	4	4	4	4	4
		1E-7	5	5	5	5	5

Case Code Format <u>A-GG-TTT-P</u>

A = Fin and Support tube Material, and Geometry (A-E)
G = Gas type (HE or H2)
T = Temperature Range (08,22,85 K)
P = Pressure Range (1-5)

Table 2.3 On Conductance, Off Conductance, 'Switch Ratio' Computed by HTSWTCH for Various Off Pressures, Gases, and Temperatures

CONDITION	P_{off}(Torr)	SWITCH RATIO	K_{on}(W/K)	K_{off}(W/K)
C-HE-09 K	1.00E-03	158	4.23	2.67E-02
C-HE-09 K	1.00E-04	1438	4.23	2.94E-03
C-HE-09 K	1.00E-05	7519	4.23	5.63E-04
C-HE-09 K	1.00E-06	12980	4.23	3.26E-04
C-HE-09 K	1.00E-07	14000	4.23	3.02E-04
C-HE-22 K	1.00E-03	933	7.62	8.17E-03
C-HE-22 K	1.00E-04	4540	7.62	1.68E-03
C-HE-22 K	1.00E-05	7403	7.62	1.03E-03
C-HE-22 K	1.00E-06	7902	7.62	9.64E-04
C-HE-22 K	1.00E-07	7955	7.62	9.58E-04
C-HE-85 K	1.00E-03	2307	13.2	5.73E-03
C-HE-85 K	1.00E-04	3462	13.2	3.82E-03
C-HE-85 K	1.00E-05	3644	13.2	3.63E-03
C-HE-85 K	1.00E-06	3663	13.2	3.61E-03
C-HE-85 K	1.00E-07	3665	13.2	3.61E-03
C-H_2-22 K	1.00E-03	130	4.79	3.68E-02
C-H_2-22 K	1.00E-04	1057	4.79	4.53E-03
C-H_2-22 K	1.00E-05	3654	4.79	1.31E-03
C-H_2-22 K	1.00E-06	4827	4.79	9.95E-04
C-H_2-22 K	1.00E-07	4989	4.79	9.60E-04
C-H_2-85 K	1.00E-03	1229	11.8	9.62E-03
C-H_2-85 K	1.00E-04	2816	11.8	4.20E-03
C-H_2-85 K	1.00E-05	3234	11.8	3.65E-03
C-H_2-85 K	1.00E-06	3271	11.8	3.62E-03
C-H_2-85 K	1.00E-07	3276	11.8	3.60E-03

Table 2.3 (Cont'd.) On Conductance, Off Conductance, 'Switch Ratio' Computed by HTSWTCH for Various Off Pressures, Gases, and Temperatures

CONDITION	P_{off}(Torr)	SWITCH RATIO	K_{on}(W/K)	K_{off}(W/K)
D-HE-09 K	1.00E-04	1438	4.23	2.94E-03
D-HE-09 K	1.00E-05	7510	4.23	5.64E-04
D-HE-09 K	1.00E-06	13000	4.23	3.26E-04
D-HE-09 K	1.00E-07	14020	4.23	3.02E-04
D-HE-22 K	1.00E-04	4562	7.62	1.67E-03
D-HE-22 K	1.00E-05	7462	7.62	1.02E-03
D-HE-22 K	1.00E-06	7968	7.62	9.55E-04
D-HE-22 K	1.00E-07	8023	7.62	9.50E-04
D-HE-85 K	1.00E-04	3968	13.2	3.34E-03
D-HE-85 K	1.00E-05	4209	13.2	3.14E-03
D-HE-85 K	1.00E-06	4235	13.2	3.12E-03
D-HE-85 K	1.00E-07	4237	13.2	3.12E-03
D-H_2-22 K	1.00E-04	1058	4.79	4.53E-03
D-H_2-22 K	1.00E-05	3666	4.79	1.31E-03
D-H_2-22 K	1.00E-06	4866	4.79	9.85E-04
D-H_2-22 K	1.00E-07	5031	4.79	9.50E-04
D-H_2-85 K	1.00E-04	3176	11.8	3.72E-03
D-H_2-85 K	1.00E-05	3717	11.8	3.18E-03
D-H_2-85 K	1.00E-06	3782	11.8	3.12E-03
D-H_2-85 K	1.00E-07	3788	11.8	3.12E-03

Table 2.3 (Cont'd.) On Conductance, Off Conductance, 'Switch Ratio' Computed by HTSWTCH for Various Off Pressures, Gases, and Temperatures

CONDITION	P_{off} (Torr)	SWITCH RATIO	K_{on} (W/K)	K_{off} (W/K)
E-HE-09 K	1.00E-04	1515	4.23	2.79E-03
E-HE-09 K	1.00E-05	10220	4.23	4.14E-04
E-HE-09 K	1.00E-06	24040	4.23	1.76E-04
E-HE-09 K	1.00E-07	27800	4.23	1.52E-04
E-HE-22 K	1.00E-04	6372	7.62	1.20E-03
E-HE-22 K	1.00E-05	13930	7.62	5.45E-04
E-HE-22 K	1.00E-06	15810	7.62	4.82E-04
E-HE-22 K	1.00E-07	16030	7.62	4.76E-04
E-HE-85 K	1.00E-04	7416	13.2	1.78E-03
E-HE-85 K	1.00E-05	8307	13.2	1.59E-03
E-HE-85 K	1.00E-06	8408	13.2	1.57E-03
E-HE-85 K	1.00E-07	8418	13.2	1.57E-03
E-H_2-22 K	1.00E-04	1181	4.79	4.06E-03
E-H_2-22 K	1.00E-05	5753	4.79	8.35E-04
E-H_2-22 K	1.00E-06	9387	4.79	5.10E-04
E-H_2-22 K	1.00E-07	10020	4.79	4.80E-04
E-H_2-85 K	1.00E-04	5440	11.8	2.18E-03
E-H_2-85 K	1.00E-05	7249	11.8	1.63E-03
E-H_2-85 K	1.00E-06	7499	11.8	1.58E-03
E-H_2-85 K	1.00E-07	7525	11.8	1.57E-03

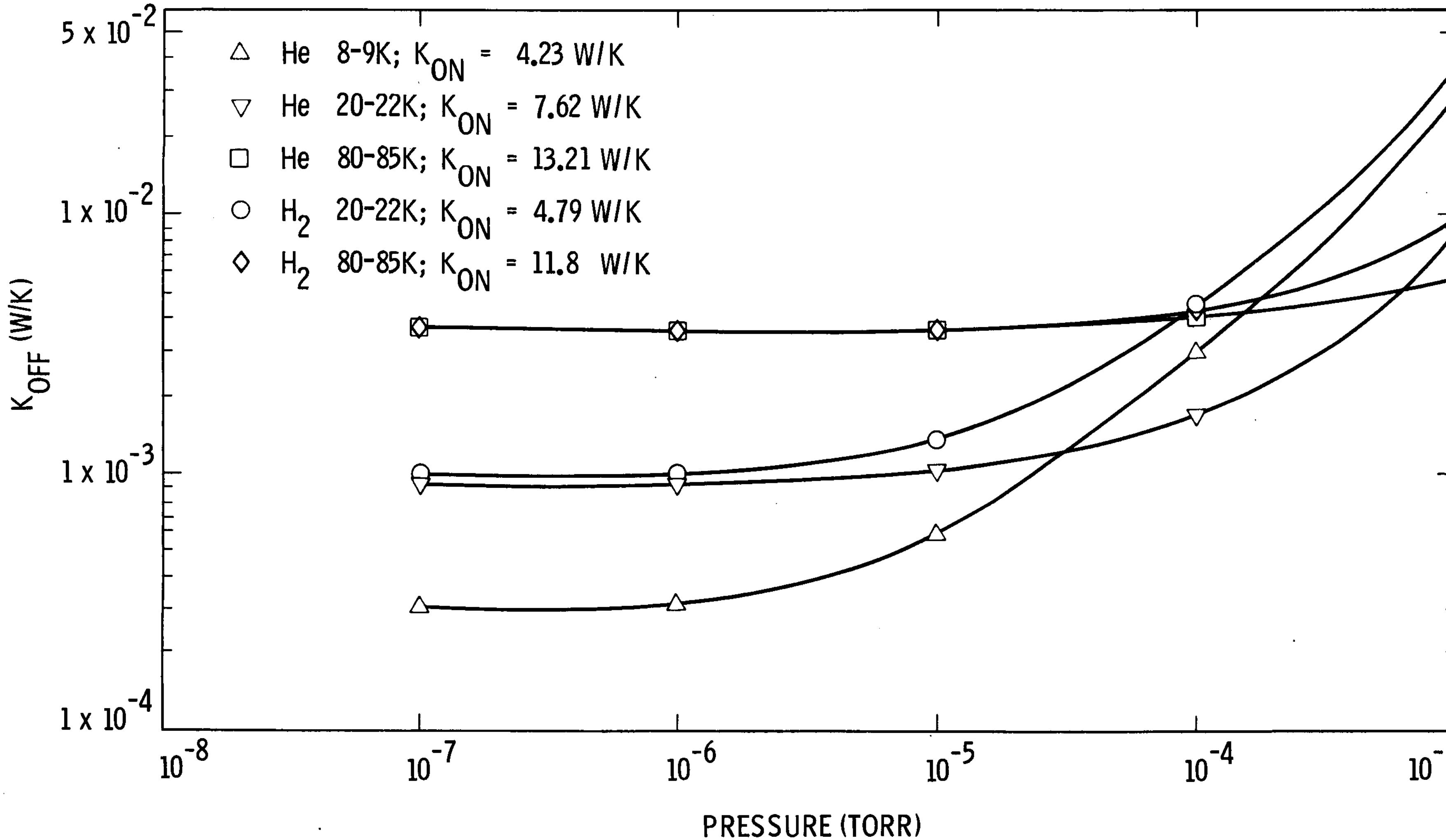

Figure 2.13. Off Conductance as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.4 Surface Emissivity in a 0.0102 cm Thick Stainless Steel Tube (Case C)

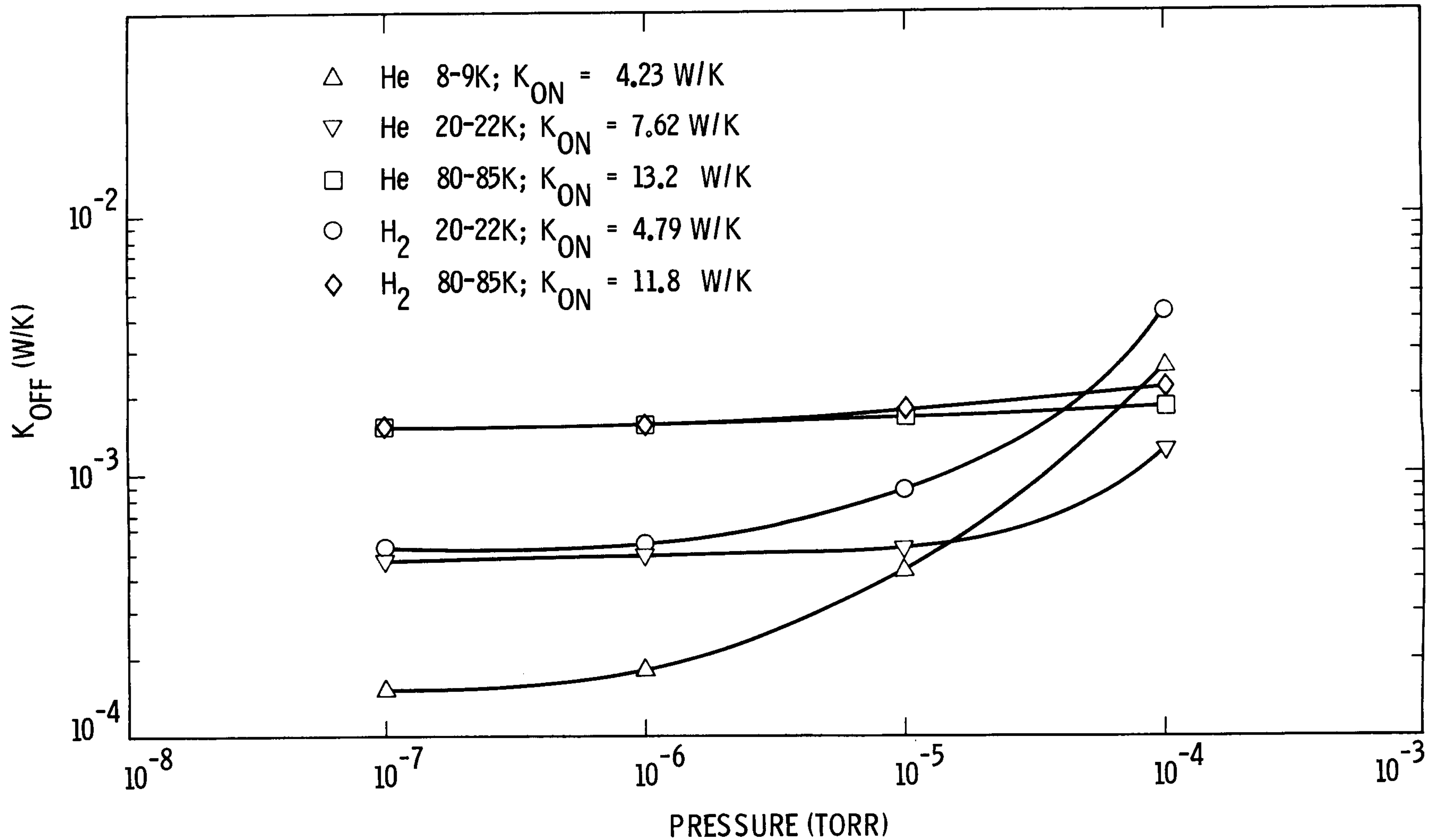

Figure 2.14. Off Conductance as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.02 Surface Emissivity in a 0.0102 cm Thick Stainless Steel Tube (Case D)

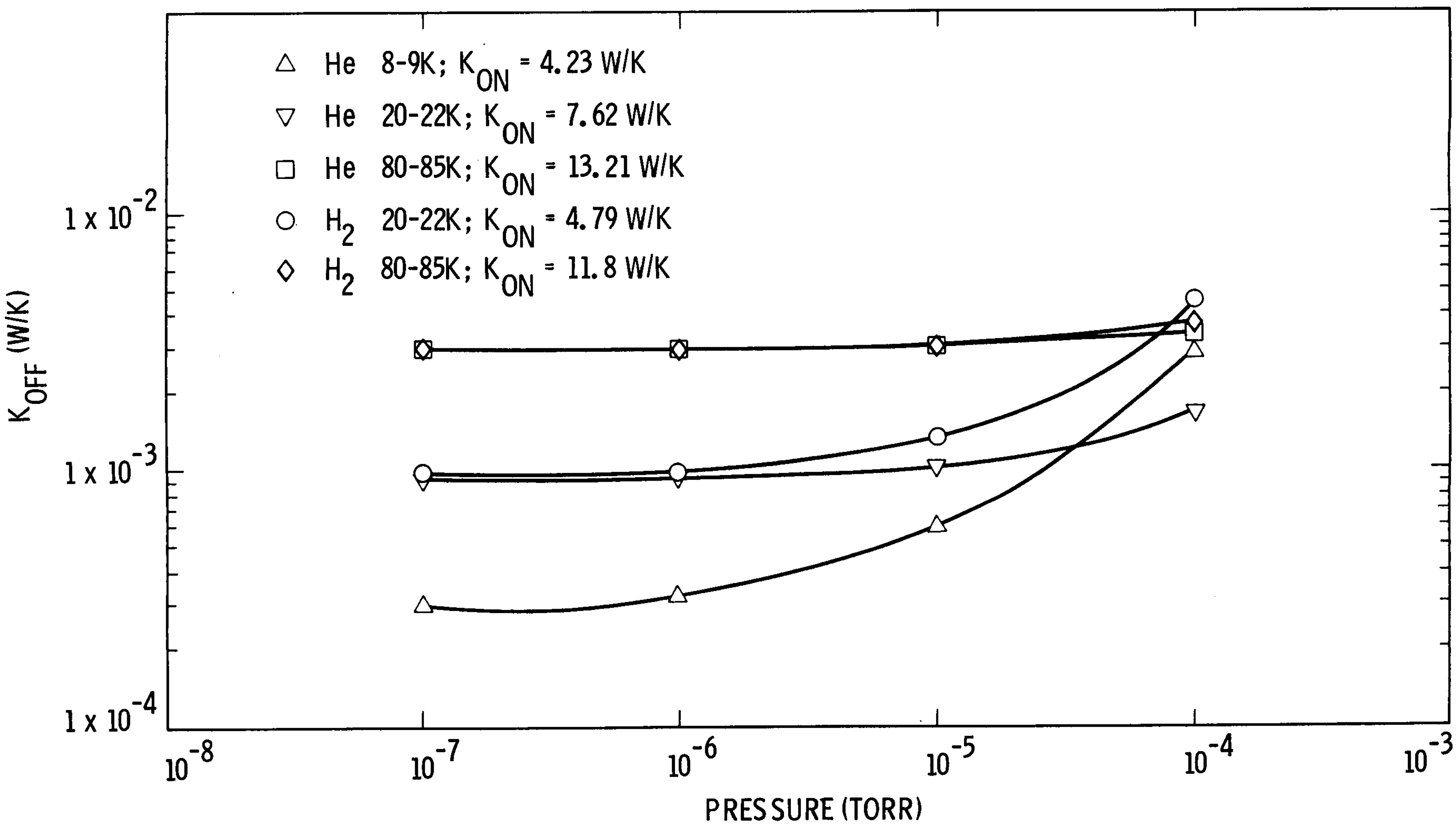

Figure 2.15. Off Conductance as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.02 Surface Emissivity in a 0.0051 cm Thick Stainless Steel Tube (Case E)

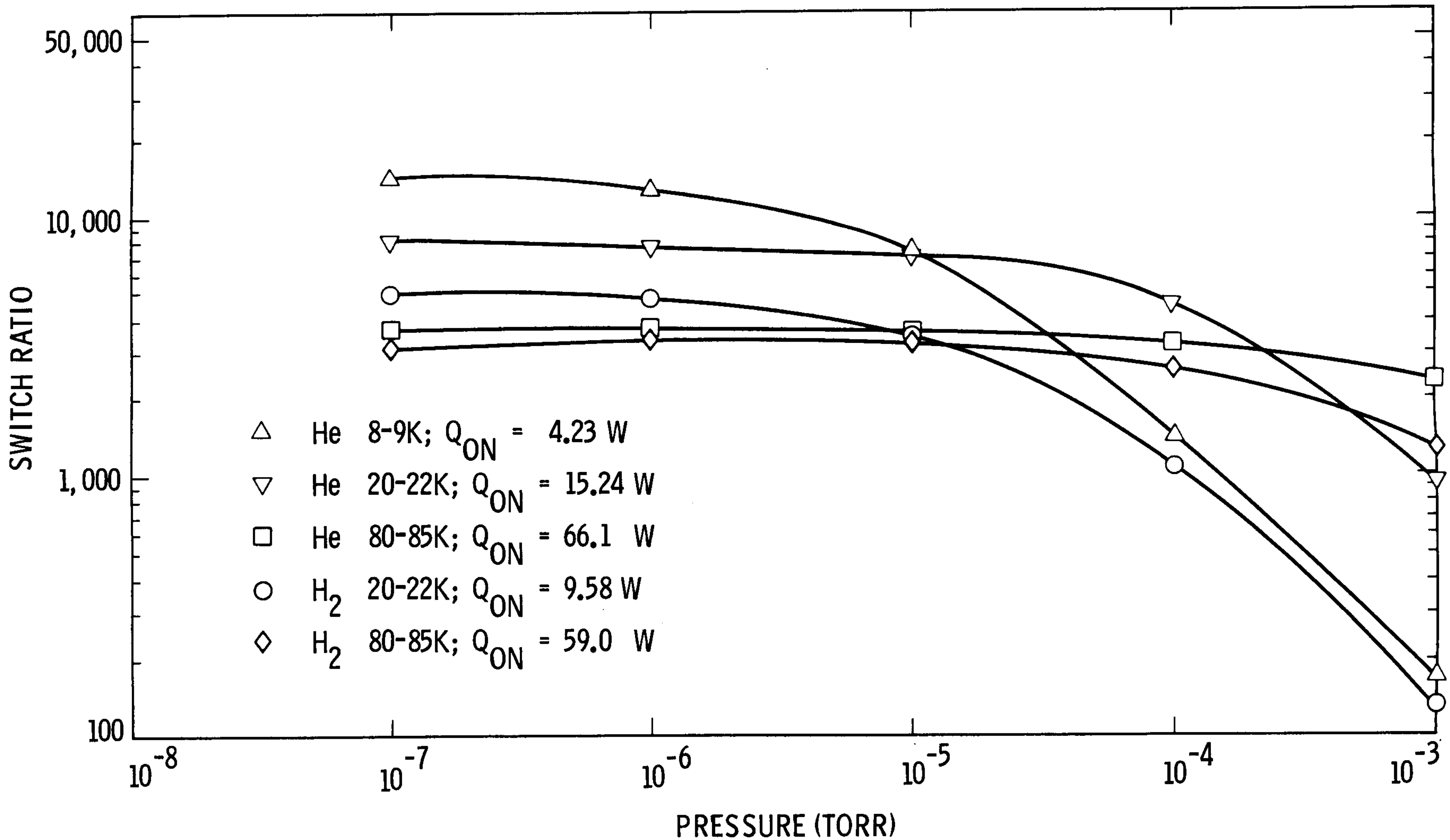

Figure 2.16. Switch Ratios and Heat Flow as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.4 Surface Emissivity in a 0.0102 cm Thick Stainless Steel Tube (Case C)

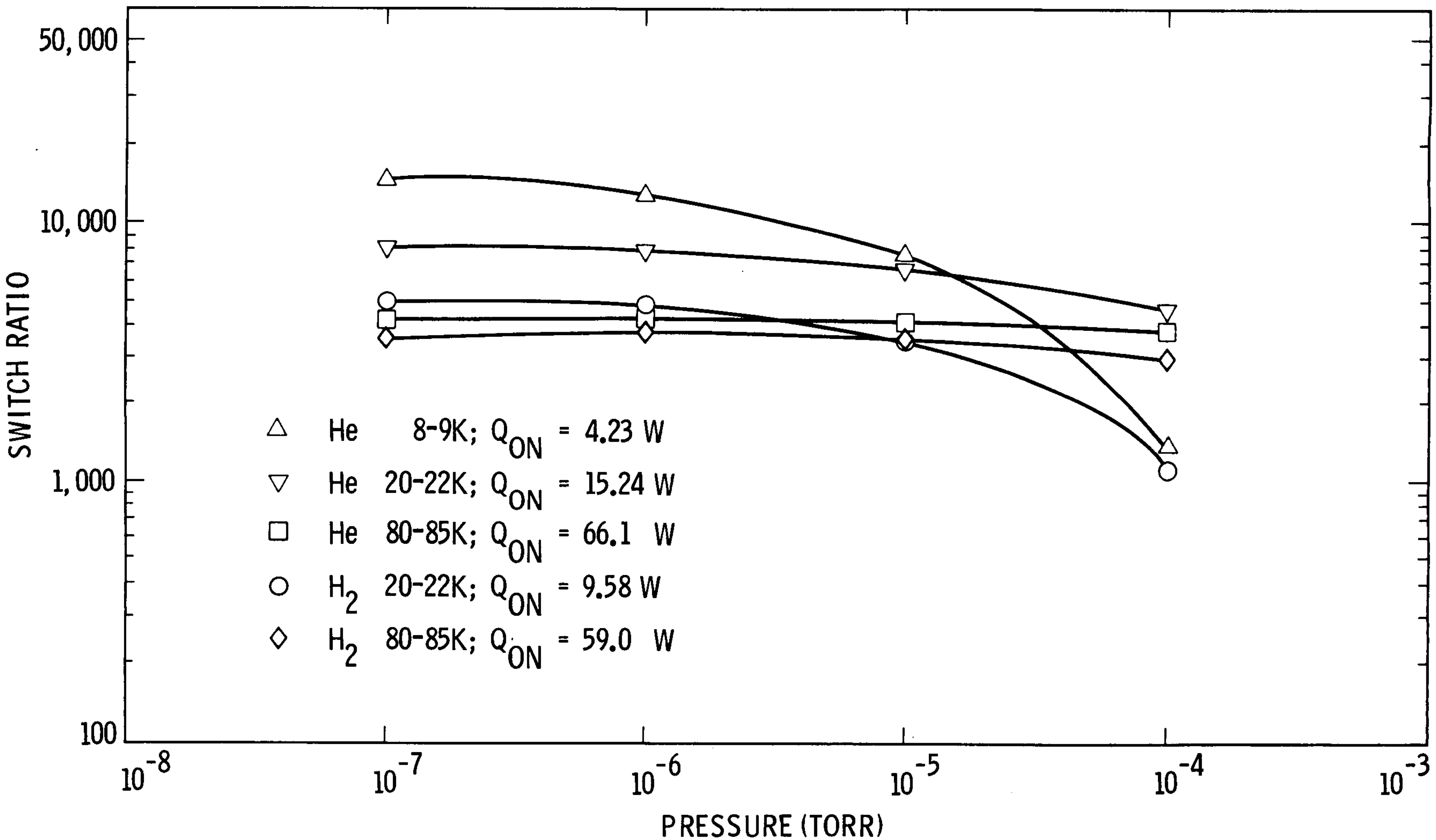

Figure 2.17. Switch Ratios and Heat Flow as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.02 Surface Emissivity in a 0.002 cm Thick Stainless Steel Tube (Case D)

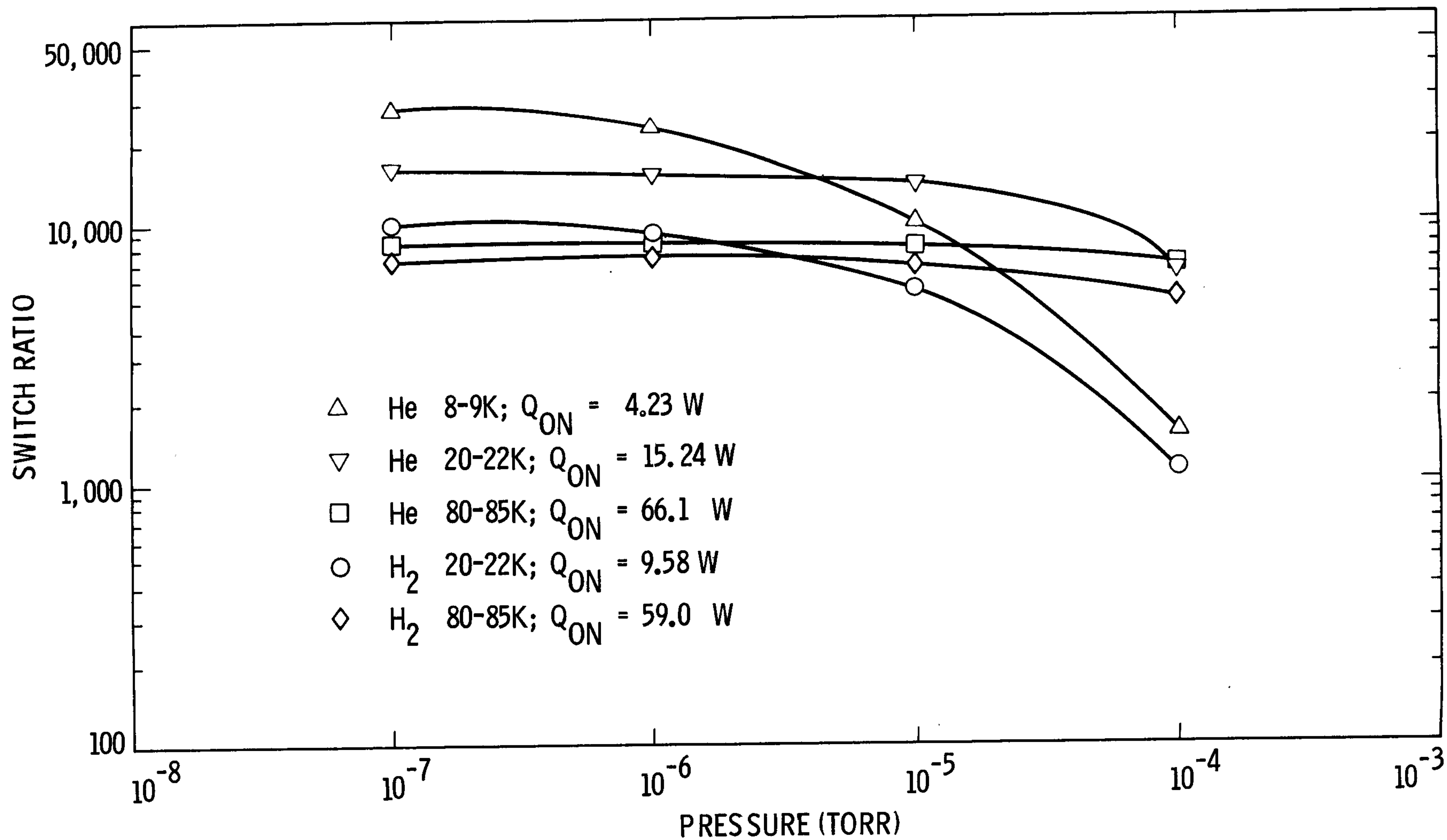

Figure 2.18. Switch Ratios and Heat Flow as Functions of Gas Pressures, Temperatures, and Gases for Straight Fins of 0.02 Surface Emissivity in a 0.0051 cm Thick Stainless Steel Tube (Case E)

(1) The helium gas switch, in general, has better performance than the hydrogen gas switch.

(2) At 80 K when the pressure is less than 10^{-4} torr, the radiation is dominant while at lower temperatures (e.g., 10 and 20 K) the radiation can be neglected until the pressure is less than 10^{-6} torr. This agrees in general with the results shown in Fig. 2.3.

(3) Hence, the off-conductance and the switch ratio are limited by surface emissivity and support conductance. A switch ratio of 30,000 at 10 K can be achieved with 0.02 surface emissivity and 0.0051 cm thick stainless steel tube.

(4) A comparison with the results of the pie fin design (Fig. 2.19) indicates that the heat switch with the straight fin design has better performance.

Based on these analyses, the straight fin design was selected for fabrication.

Since one of the major heat leaks during the off mode is through the support tube, it is essential in designing the tube that the cross-sectional area should be small, the length where it touches the two copper pieces should be long, and the thermal conductivity of the material should be low. Four designs were under consideration: a 2-mil and a 4-mil thick stainless steel tube, a 40 mil thick G-10 tube with a 0.5-mil thick stainless steel lining, and a 40 mil thick glass tube. The plottings of the thermal resistance of the supporting tubes versus temperatures for the designs are shown in Fig. 2.20. At low temperatures the stainless steel tubes has the highest thermal resistance, but it has the lowest value at 80 K.

In addition to the thermal resistance, other factors were also considered. For example, the glass tube would have the potential of helium leakage at room temperature. The G-10 tube with the stainless steel lining would eliminate this leakage. However, the G-10 material may not be acceptable in the system because of the outgas problem. Since the 4 mil stainless steel tube has fairly good thermal resistance, it was chosen for fabrication. The 2 mil thick stainless steel tube will be used as long as it imposes no structural problem to the heat switch.

2.4 Sorption Pump Design

The adsorption pump acts as a source and sink for the gas. It is operated by heating and cooling the adsorber which causes gas to be either released or readsorbed, respectively. A number of materials can be used as adsorbers. In a heat switch where the thermal conductivity of the gas is important, the most appropriate gases for use are helium and hydrogen (Fig. 2.4).

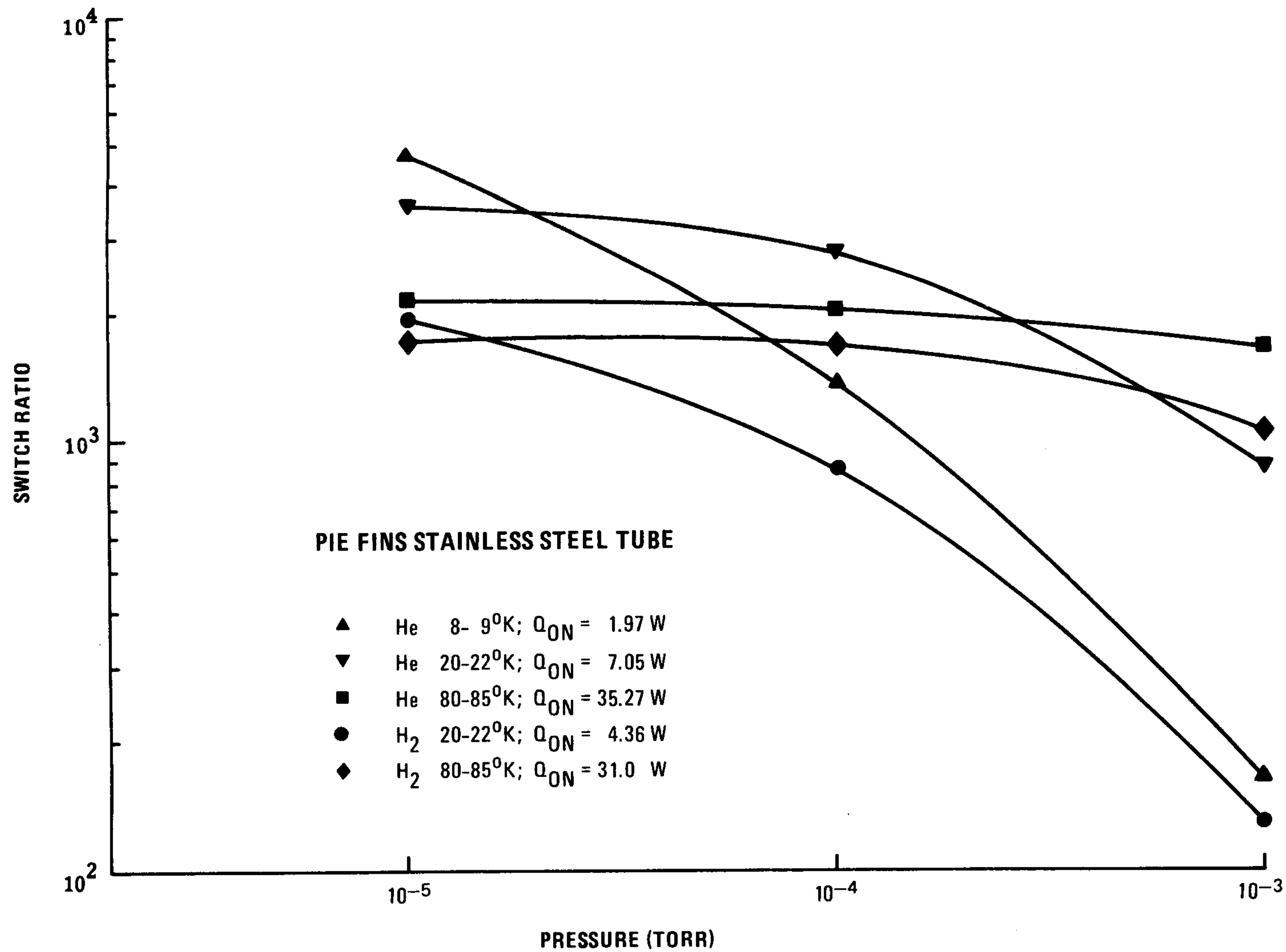

Figure 2.19. Switch Ratio and Heat Flow as Functions of Gas Pressures, Temperatures and Gases for Pie Fins of 0.4 Surface Emissivity in a 0.0102 cm Thick Stainless Steel Tube

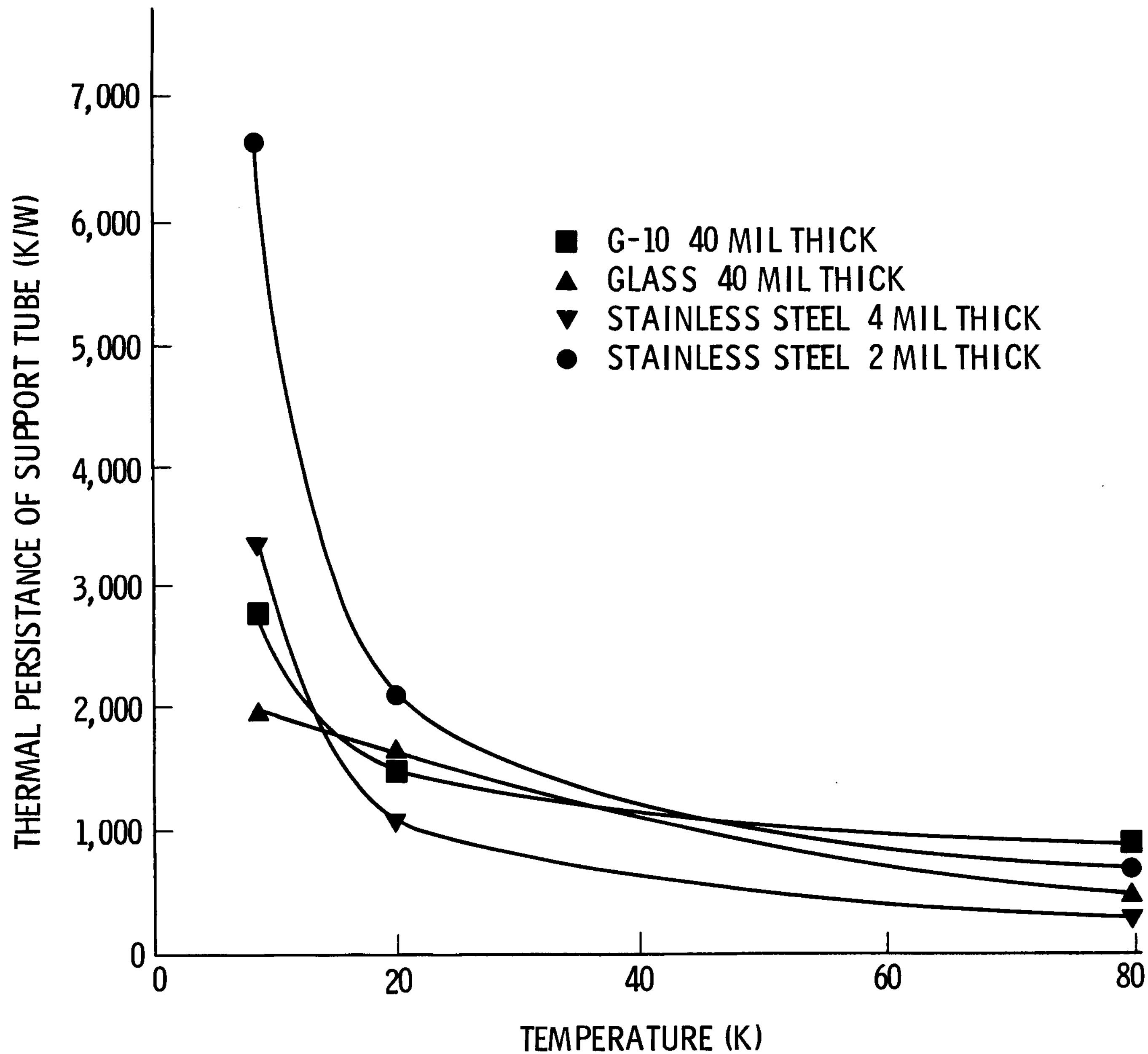

Figure 2.20. Thermal Resistance of Support Tube as Functions of Material and Temperature

These gases may be adsorbed onto charcoal or zeolite for example or, in the case of hydrogen, absorbed into metal hydrides. An important feature of the adsorbers is their extremely large effective surface areas per unit volume (500 to 3000 m^2/gm) and hence they can store liquid densities of the gas at low pressures by physical force. The amount of gas being adsorbed at a given temperature and pressure is given by the isotherms which are shown in Figs. 2.21 and 2.22 for helium and hydrogen on charcoal [2.5] and in Fig. 2.23 for hydrogen in metal hydride [2.6]. However, as shown earlier, the pressure range of the switch operation is usually in the 10^{-6} torr to a few torr range. The sorption process is based on physical force, i.e. adsorption is a better candidate to pull the vacuum. The material choice is charcoal or zeolite as the adsorbing material.

When the switch is off, the adsorber has to be held at the low temperature T_ℓ(K), so the bulk of the gas is adsorbed and the pressure is lowered to P_ℓ(torr). At that pressure the conductance across the gaps is minimal. When the absorber temperature is raised to a value of T_h, the gas pressure at the gap is increased due to the gas liberation. The pressure raises to a value of P_h where the mean free path is much smaller than the gap, i.e., the switch is on.

The quantity of the adsorber and the power required to operate the switch are functions of the temperatures T_ℓ and T_h, the pressures P_ℓ and P_h and the volume of the gas V_g.

If V_f is the gas volume between the gaps in the heat switch,

V_l = the gas volume in the line and in the system, cm^3

V_p = is the gas volume in the adsorber, cm^3

C_ℓ = mass ratio of gas being adsorbed at P_ℓ, T_ℓ,

C_h = mass ratio of gas being adsorbed at P_h, T_h

Then

$$\Delta C = C_\ell - C_h = (V_f + V_l + V_p)M/(22400\ cm^3/\text{gm mole}\ m_a) \quad (2.4.1)$$

where

M = molecular weight of the gas, gm/gm·mole

m_a = the mass quantity of the adsorber, gm

The gas volume in the adsorber is related to m_a by

$$V_p = m_a/\rho_p - m_a/\rho_a \quad (2.4.2)$$

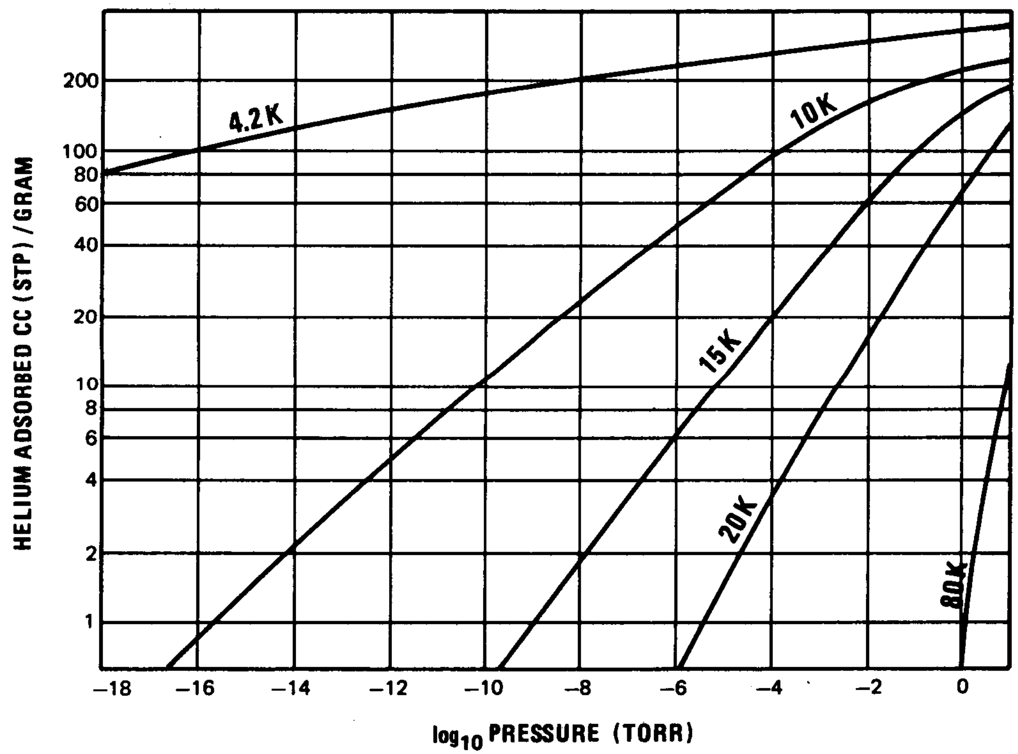

Figure 2.21. Calculated Isotherms for Helium on PCB Carbons from 4 K to 80 K

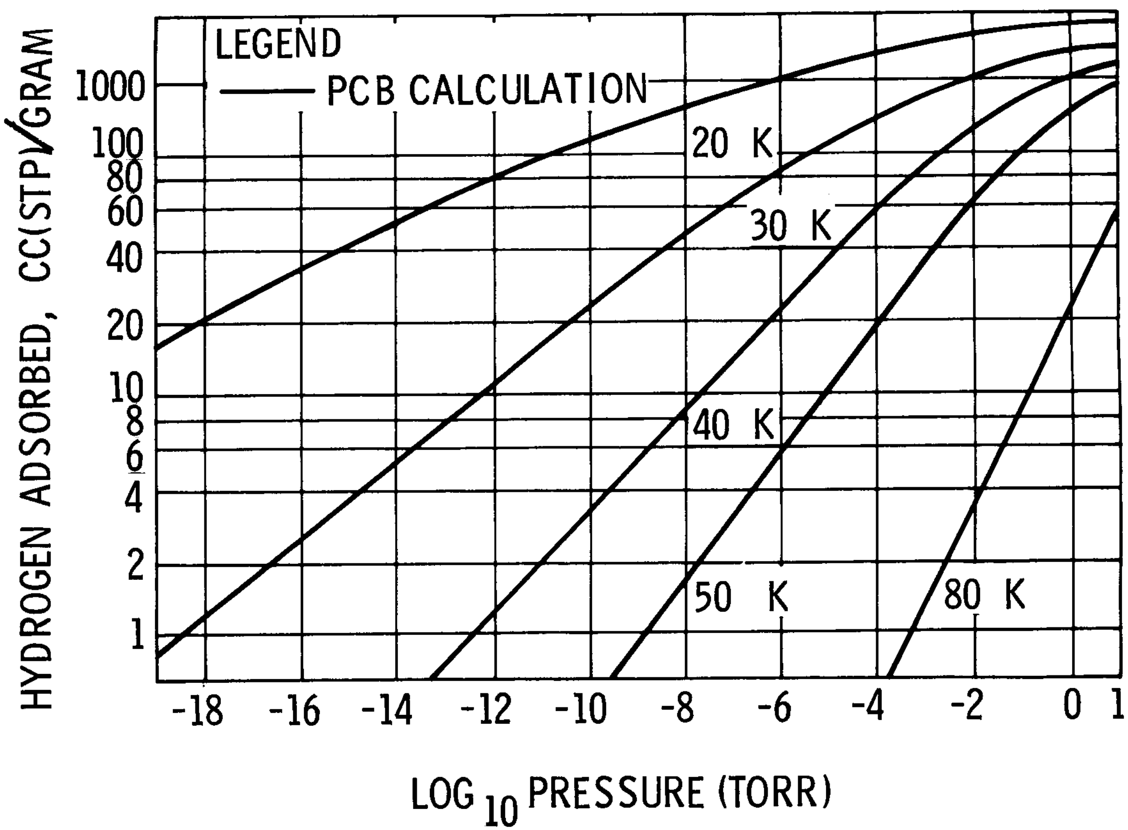

Figure 2.22. Calculated Isotherms for Hydrogen on PCB Carbons from 20 K to 80 K

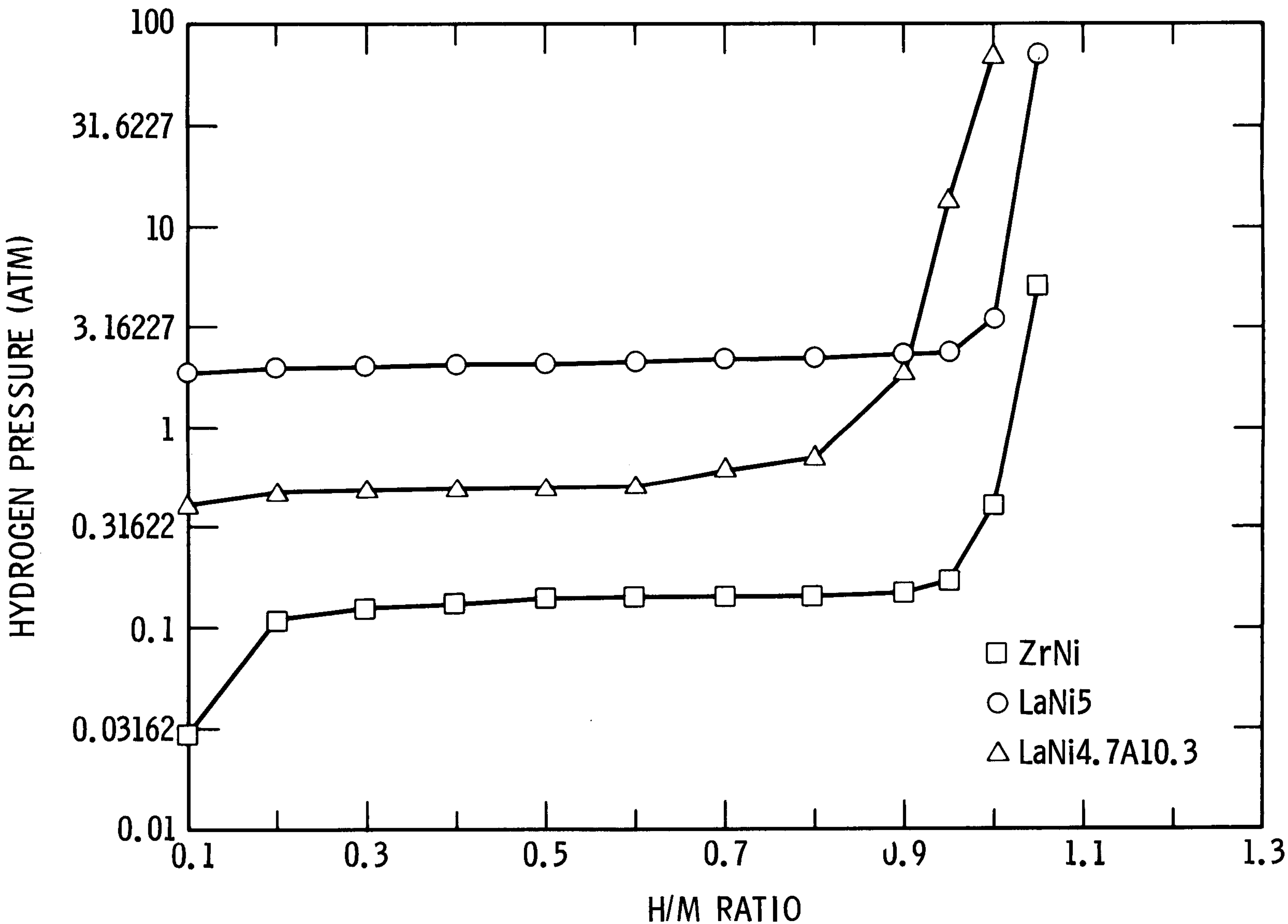

Figure 2.23. Adsorption Isotherms of Hydrides

where

ρ_p = bulk density of the adsorber, gm/cc

ρ_a = molecular density of the adsorber, gm/cc

Substituting equation (2.4.2) into equation (2.4.1), the mass quantity is given by

$$m_a = (V_f + V_1)M/[22400\ \mathrm{cm^3/gm{\cdot}mole}\ \Delta C - (1/\rho_p - 1/\rho_a)M] \quad (2.4.3)$$

The energy required to turn the switch from the off mode to the on mode is

$$E_s = m_a C_{pa} \Delta T + m_a \Delta C \Delta u + m_a \Delta C C_{pg} \Delta T + m_p C_{pp} \Delta T \quad (2.4.4)$$

where

the first term is the heatup for the adsorber

m_a = mass, gm

C_p = heat capacity, J/gmK

$\Delta T = T_h - T_\ell$, K

the second term is the heat for the gas liberation,

Δu = heat of desorption, J/gm

the third term is the heatup for the gas, and

C_{pg} = heat capacity of the gas, J/gmK

the fourth term is the heatup for the pump structure

m_p = pump mass, gm

C_{pp} = heat capacity, J/gmK.

If the pump is thermally linked to a heat sink of temperature T_s (Fig 2.1), the power required to operate the switch is also a function of the switching time required. For rapid turn-off time the thermal resistance of the thermal link must be reduced, thus causing an increased heat load at the temperature T_s and increased power requirement to turn the switch on. At steady state, the power required to keep the switch on is

$$Q_{hs} = K_{hs}\ (T_h - T_s) \quad (2.4.5)$$

where

K_{hs} = conductance of the thermal link, W/K.

However, all this power would not be necessary if the switch operation were actuated by the change of the heat sink temperature from T_s to T_h. This self-actuating concept will be discussed in Section 2.5.

This design methodology of the sorption pump is the base of the computer code "ADPUMP." The listing and a sample run are presented in Appendix B. The input parameters for the design computer code include the choice of sorption materials, the working gas, the heat switch gas volume, and the operating conditions of the heat switch. The outputs are the volume and the mass of the sorption material, as well as the energy required to power the pump at different temperature levels.

In order to ensure that the pump could create the low gas pressure as required, a simple set of tests was performed. The test apparatus (Fig. 2.24) consisted of a sorption bed which was connected to the ionized gauge and the differential pressure transducer. A quantity of gas at about 5 torr was introduced to the sorption bed at room temperature. Valve (1) was then closed and the bed was cooled by cold gas. The pressure was measured by the ionized gauge while the temperature was measured by the thermal sensor. The results for the hydrogen and the helium gas are presented in Tables 2.4 and 2.5. Indeed, when the temperature changed from 100 K to 20 K, the pressure changed from 0.8 torr to 3×10^{-6} torr for hydrogen. In the case of helium, the pressure changed from 2 torr to 10^{-6} torr when the temperature changed from 40 K to 10 K.

2.5 Self-Actuating Heat Switching Concept for Redundant Cryocoolers

The thermal connection and the isolation of the two redundant cryocoolers at three temperature levels are performed by six heat switches (Fig. 2.25). The three on heat switches on the right-hand side thermally connect the cold plates to the operational refrigerator, and the three off switches on the left-hand side thermally isolate the non-operational refrigerator. Since the presence or the absence of the gas at the switches is controlled by the temperature of the adsorption pumps, the pump adsorbs gas at low temperature to create a vacuum at the heat switch gap and turns the switch off. When the pump is at higher temperature, the adsorbent liberates gas to the switch, turning it on. If the two pumps are thermally linked to the coldest stage of the cryocoolers (Fig. 2.25), the on action is actuated automatically when the temperature T_{N3} of the non-operational refrigerator increases so the adsorption pump which is thermally linked to T_{N3}

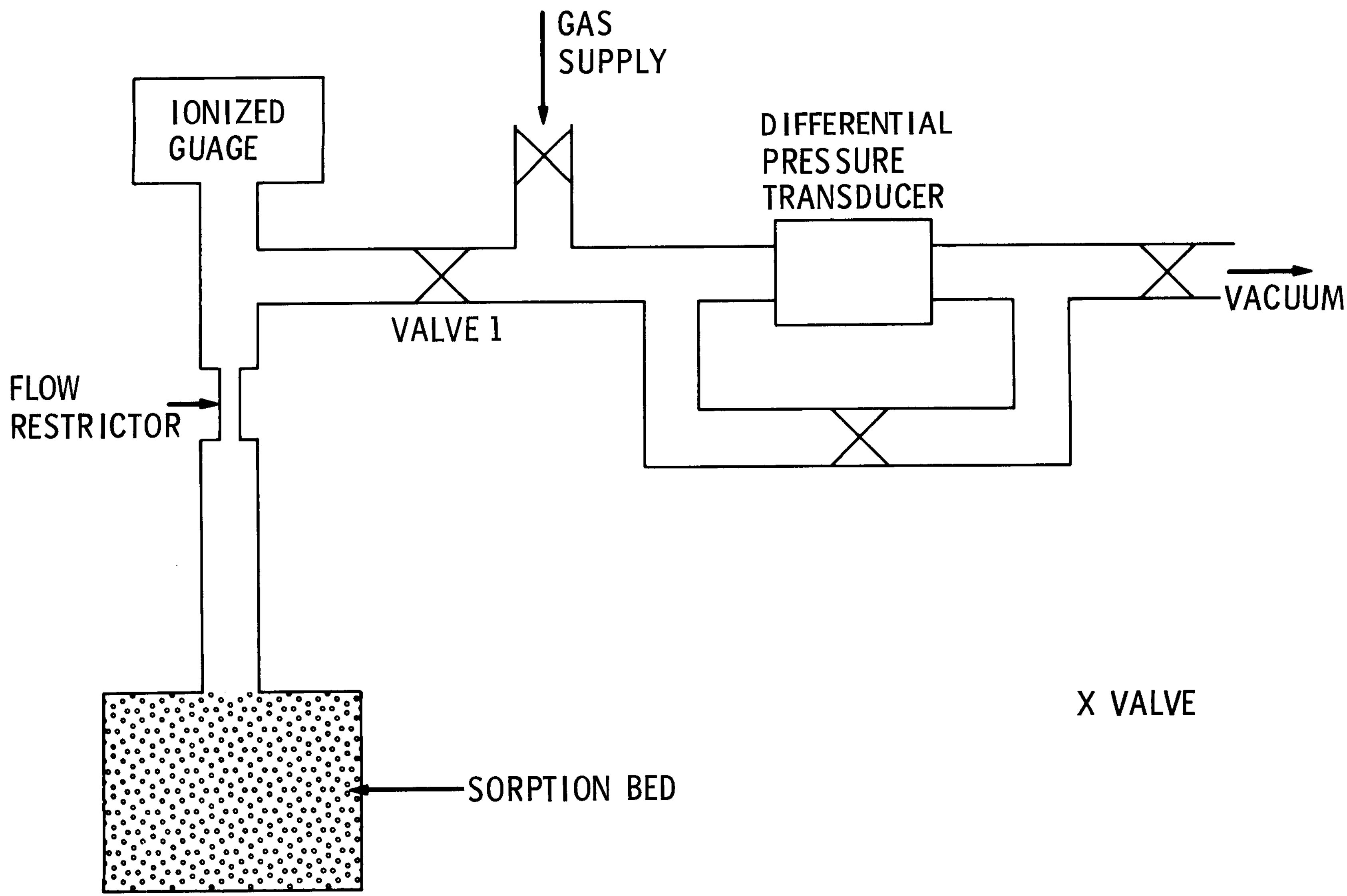

Figure 2.24. Test Apparatus for Sorption Characteristic

Table 2.4 Temperature Effects On Charcoal

Hydrogen Pump Pressure

Temperature (K)	Pressure (Torr)
268.8	5.013
200.0	2.711
140.0	2.310
100.0	8.63E−1
80.0	7.80E−2
50.0	1.1E−4
35.0	6.0E−5
30.0	3.5E−5
28.0	2.0E−5
26.0	1.0E−5
24.0	6.0E−6
22.0	4.0E−6
20.0	3.0E−6

Table 2.5 Temperature Effects On Charcoal

Helium Pump Pressure

Temperature (K)	Pressure (Torr)
298.0	5.0
40.0	1.98
28.0	1.67E−1
19.9	1.0E−3
18.0	2.5E−4
16.0	2.5E−5
13.9	3.0E−6
10.0	1.2E−6
6.0	1.0E−6
5.1	1.0E−6
4.7	6.8E−7

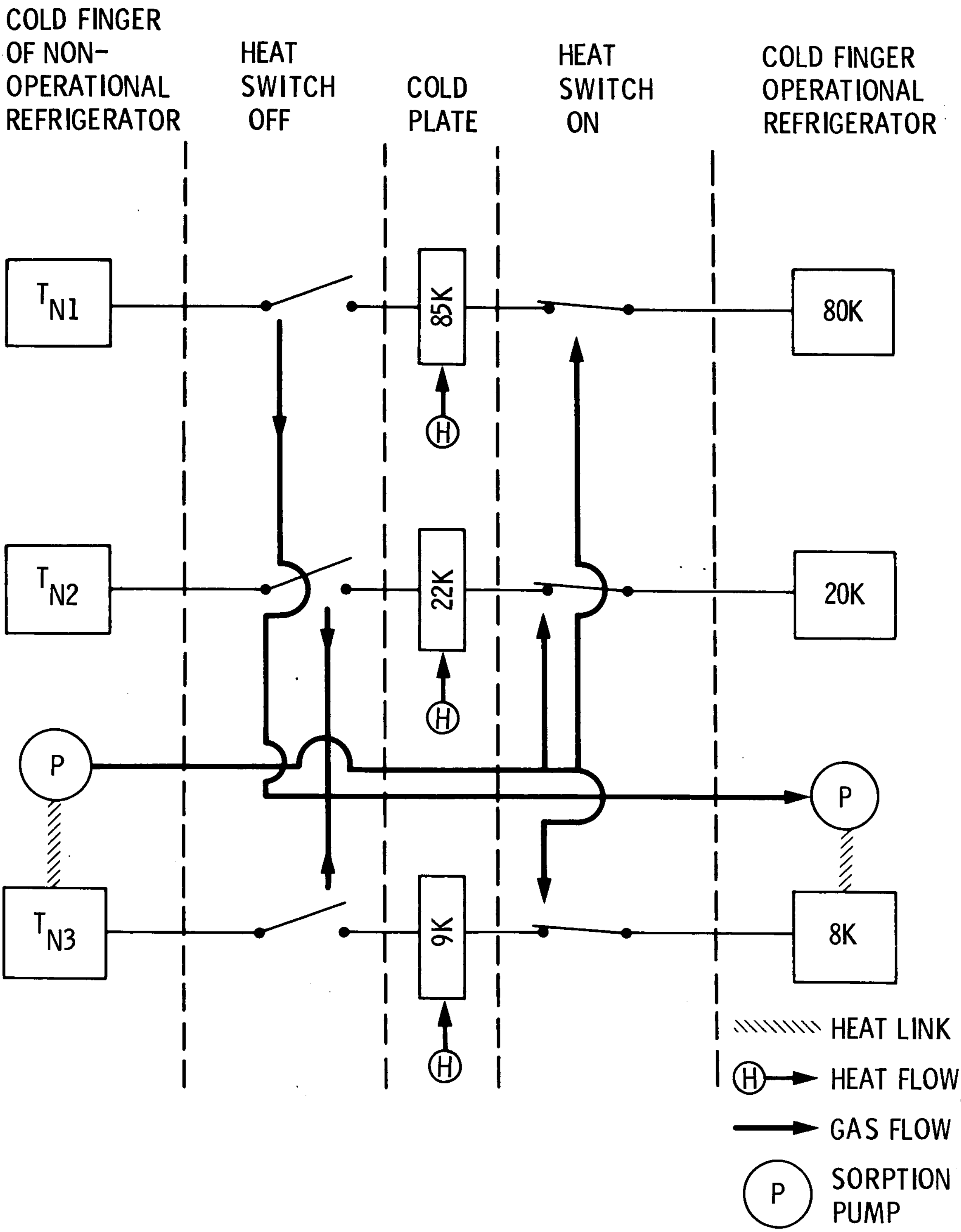

Figure 2.25. Self-Actuating Heat Switches for Two Redundant Cryocoolers

heats up and liberates the gas to the heat switches on the right-hand side. The cold stage of the operational refrigerator will keep the other pump cold, and this adsorbs the gas from the off heat switches. The switches are, hence, self-actuated by the simple temperature change at the refrigerator. However, if it is necessary to override this passive action, heaters can be installed on the pumps to control the pump temperature.

3.0 HARDWARE

The test apparatus (Fig. 3.1) was designed to measure the temperature and the heat transfer and, hence, the conductance of the switch when it is on and when it is off at temperature ranges of 10 K, 20 K, and 80 K. The heat switch and the pump (Fig. 3.2) were suspended inside a vacuum vessel. The cold side of the switch was thermally grounded to the liquid cryogen temperature at the heat sink base. For the 80 K tests the cryogen was liquid nitrogen, and for other test temperatures it was liquid helium. The outer dewar was always filled with liquid nitrogen. The base of the third dewar, in which the vacuum jacket was common to the vacuum chamber (Fig. 3.1) was thermally connected to the sorption pump heat-sink base. This dewar was attached to the top of the vacuum chamber with an indium seal. There was a high thermal resistance between the pump and the pump heat-sink base. With liquid helium inside this dewar, the heat switch pump could be operated at 10 K, while the cold side of the heat switch could be operated at 10 K, 20 K, and 80 K. There were heaters and thermal sensors attached at the hot side and the cold side of the heat switch, as well as at the pump and its heat sink base. These heaters were used to control the temperatures of the four different regions, namely the hot side and the cold side of the heat switch, the adsorption pump, and the pump base. The cross-shaped header at the heat switch assembly was connected by the gas line to the gas manifold through the valve (5), to the hot and the cold sides, and to the pump. The following sections detail the fabrication of the heat switch, the adsorption pump, and the test apparatus, together with electronic equipment and software for test control and data acquisition.

3.1 Heat Switch Fabrication

Figures 3.3 to 3.5 are the mechanical drawings showing the major components of the heat switch which consists of two copper cylinders. Grooves were cut across the surface so there were straight fins each of 0.123 inch in width protruding from the base. The base is 2.030 inches in diameter and 0.625 inch in height. The groove was four thousandths of an inch greater than the fin width, so when the two pieces were put together there were gaps of two thousandths of an inch between the fins.

The fin was 1 inch in length. Holes of 0.0625 inch in diameter were drilled at the bottom of each groove to a common 1/16" diameter channel for gas venting. As shown in Fig. 3.5, there were three screw holes on the flat surface of each cylinder. These holes were used for attachment purposes. The two copper cylinders were machined exactly identical to each other. The two pieces were held together by a stainless steel supporting tube.

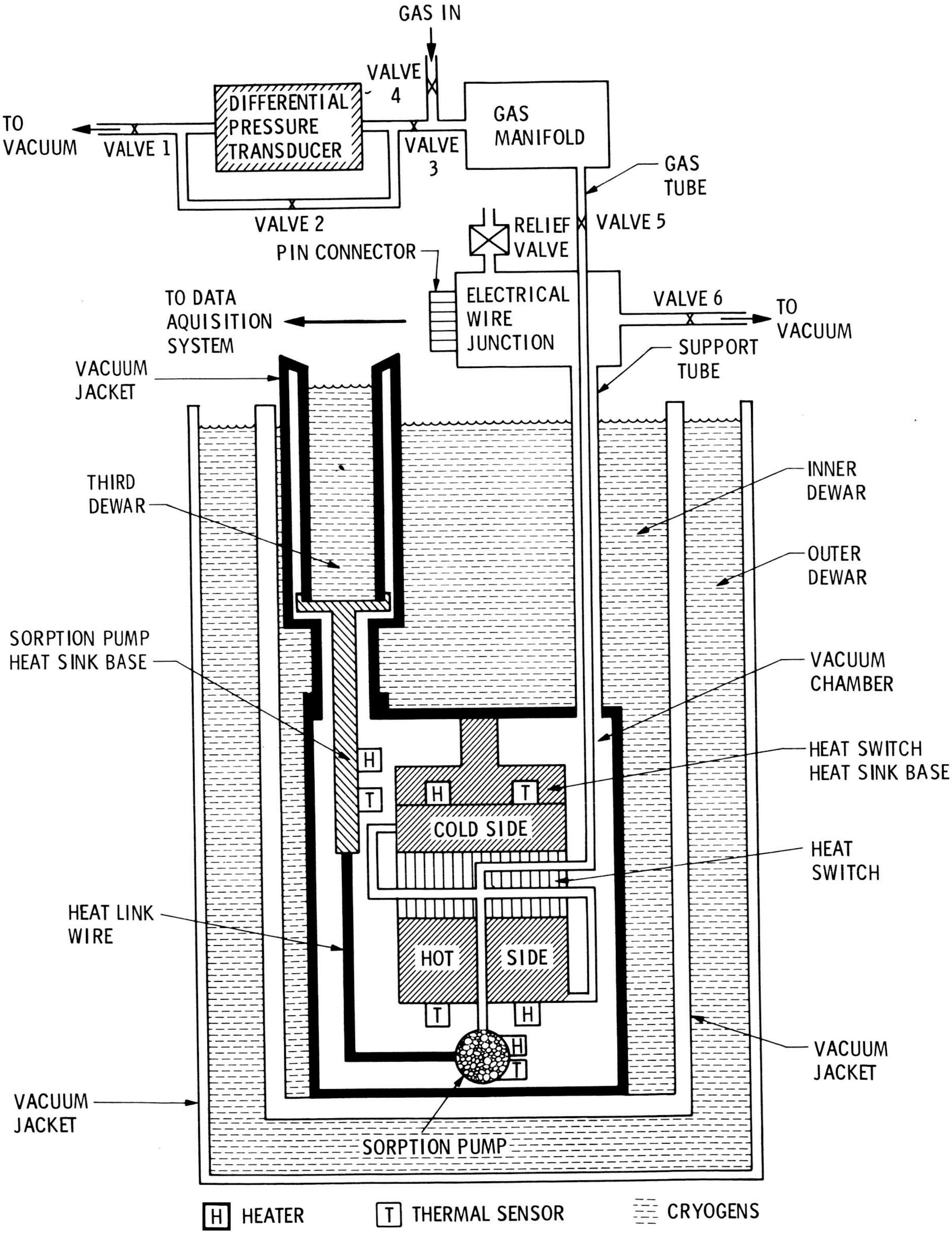

Figure 3.1. Test Apparatus

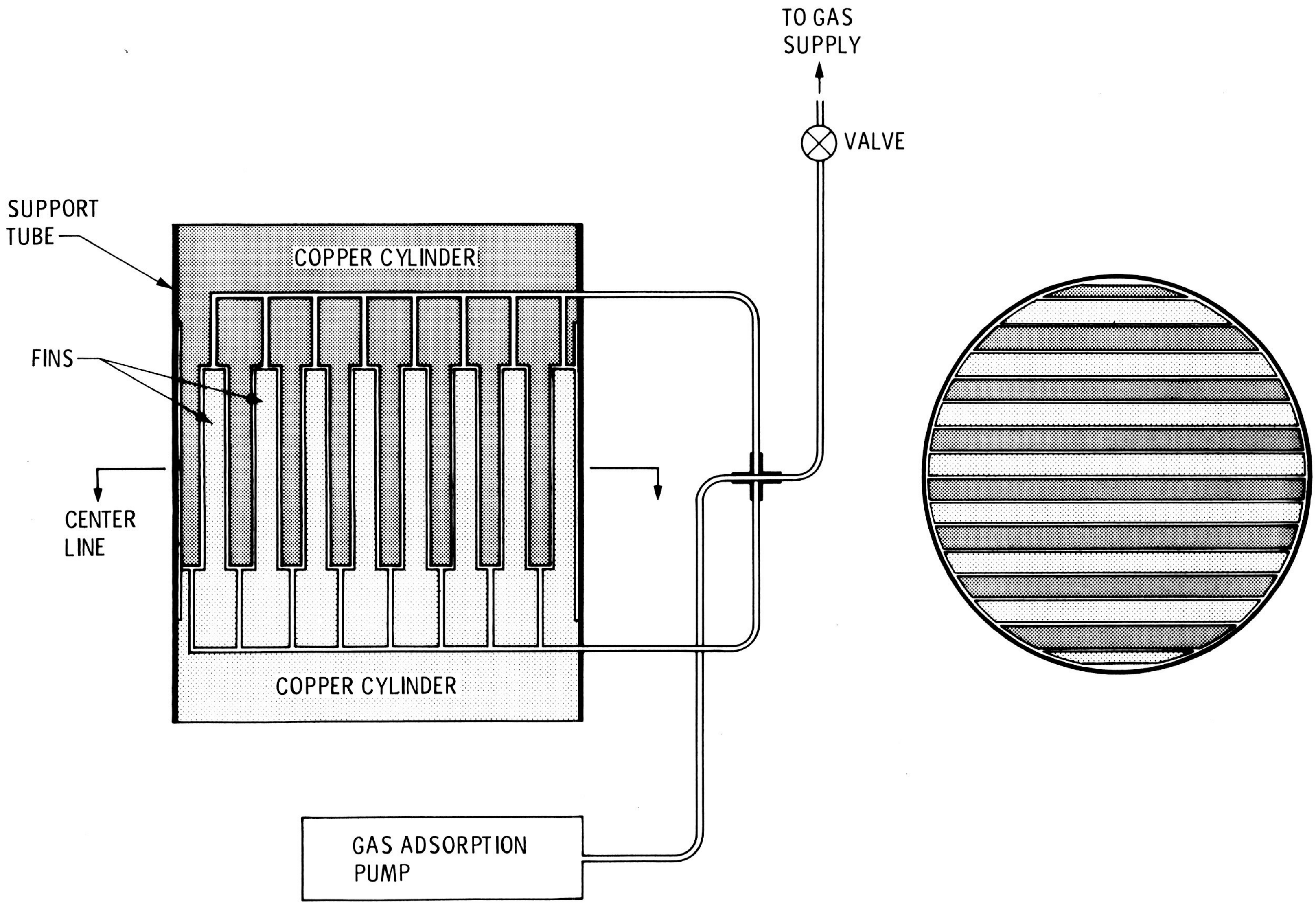

Figure 3.2. Heat Switch

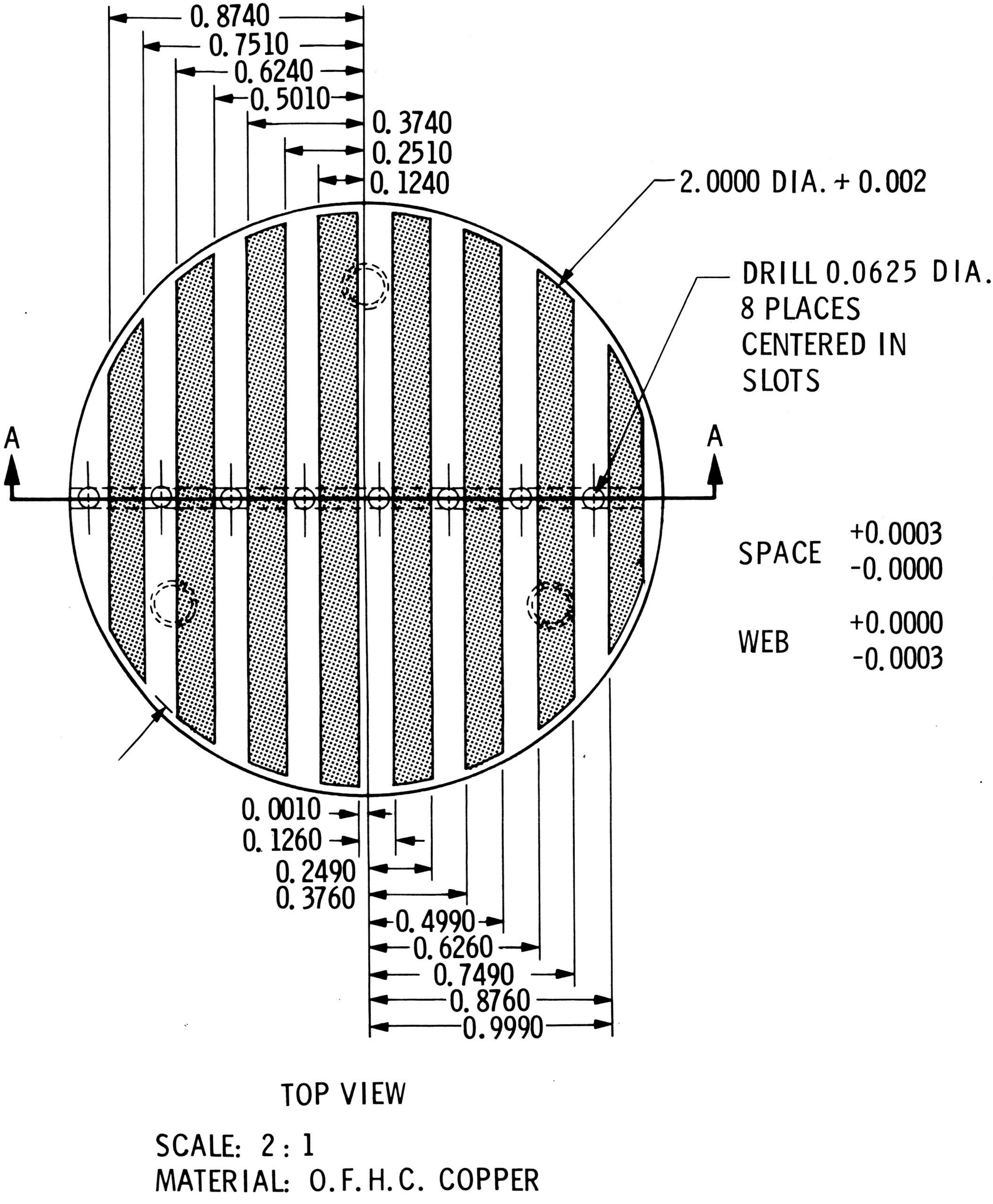

Figure 3.3 Heat Switch Cylinder with Extended Fins
(All measurements in inches)

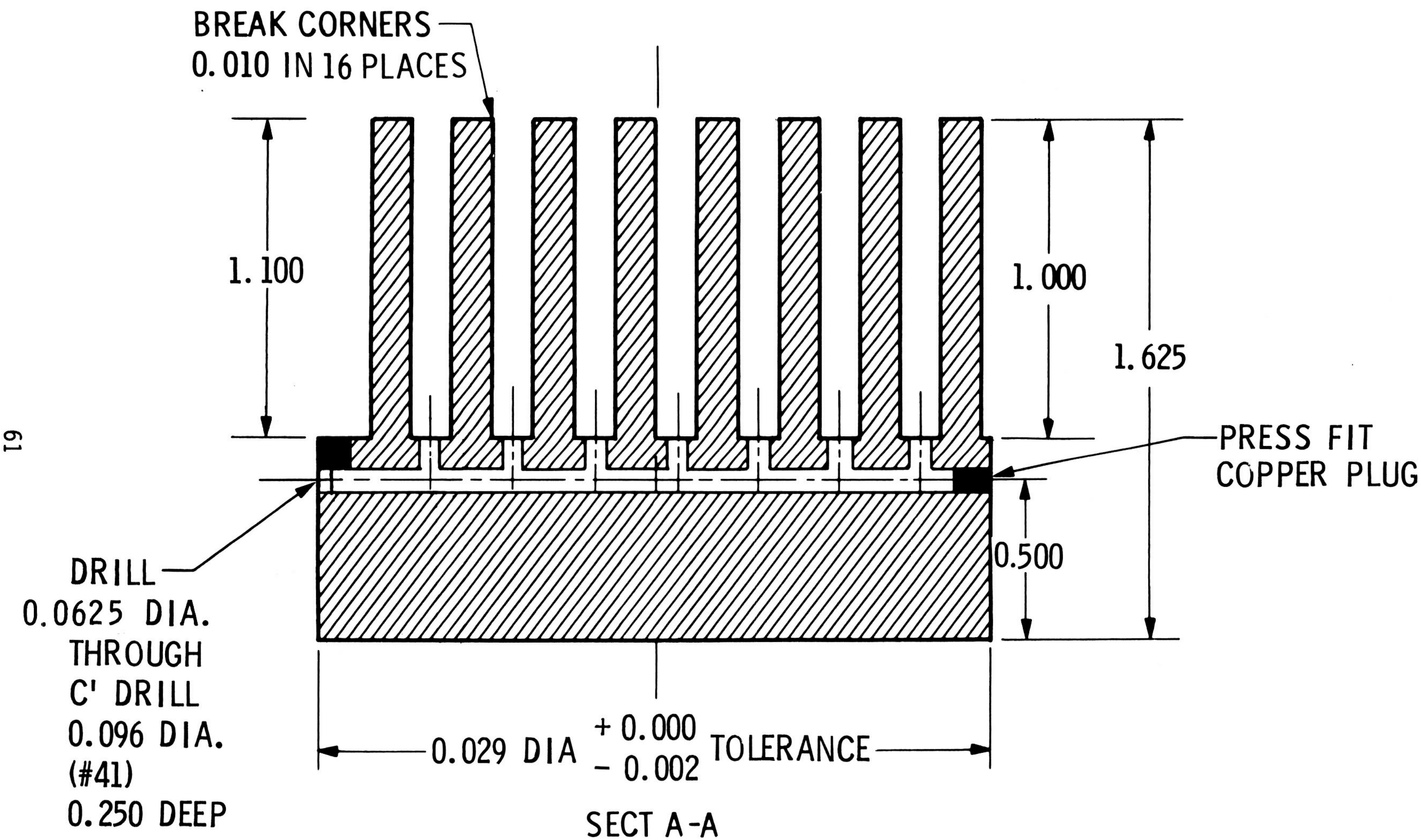

Figure 3.4. Section A-A View of Heat Switch Cylinder

(All measurements in inches)

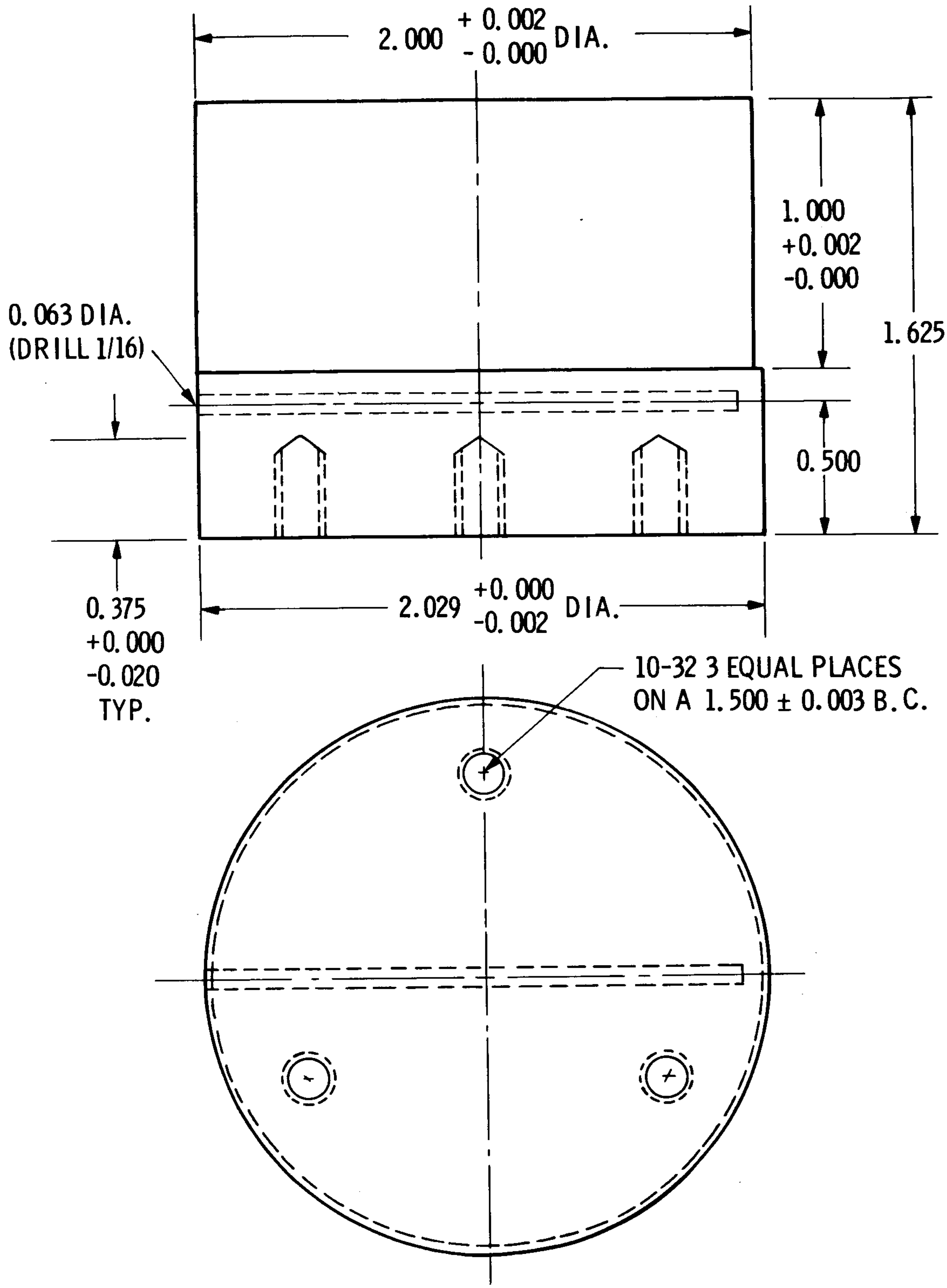

Figure 3.5. Screw Holes on Heat Switch Cylinder

(All measurements in inches)

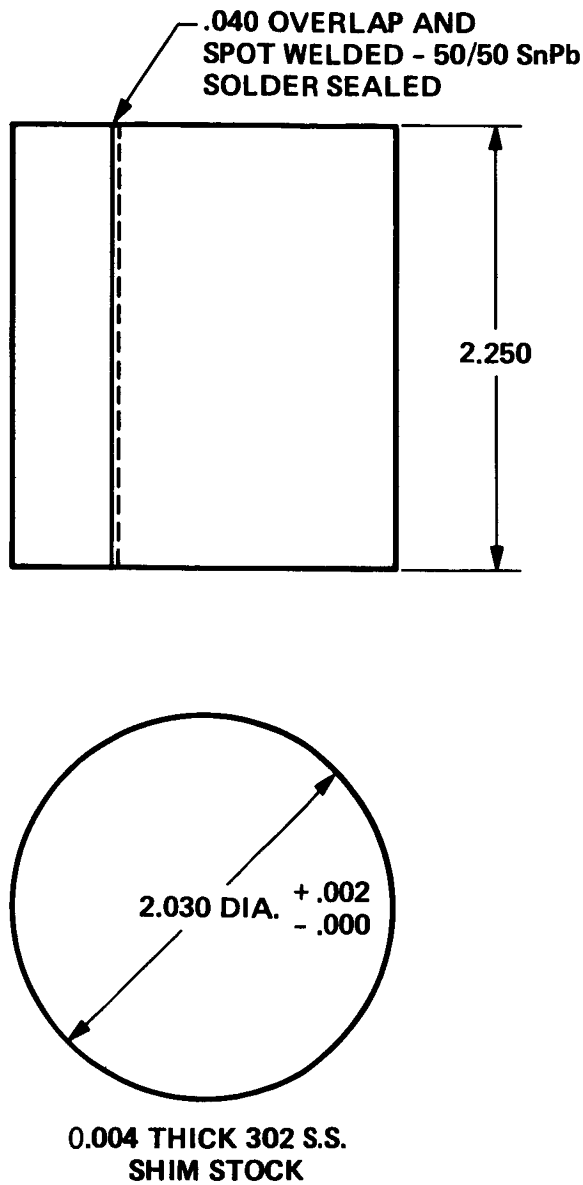

Figure 3.6. Stainless Steel Support Tube

(All measurements in inches)

The support tube (Fig. 3.6) is 2.030 inches in diameter, 2.250 inches in length, and 0.004 inch in thickness. It was made from a 302 stainless steel shim stock and spot-welded into the tube form. A photo of the finned cylinders and the stainless steel tube is shown in Fig. 3.7. The grooves shown on the flat surface are for the leads of the thermal sensors. The groove is 0.063 inch wide, 0.20 inch deep and 0.75 inch long. It runs from the edge to a hole of 0.125 inch in diameter and 0.5 inch deep. The sensor is embedded inside the hole. There are two sensors on each surface, to ensure two redundant temperature measurements.

The two copper cylinders were inserted into the support tube with their fins interlocking (Fig. 3.8). Wires of 0.002 inch in diameter were used in sizing the gaps in-between the fins, and also the gaps at the bottom end of the grooves. This assured that two cylinders did not touch. When the cylinders were at the right positions, they were soldered onto the support tube along the circumference of the base. Two heaters, with a total resistance of 100.4 Ω, were attached onto the flat surface at one end (the hot side) while the other end (the cold side) would be attached onto the heat sink base. Two stainless steel tubes of 0.0625 inch in diameter were soldered onto the two gas channels coming out from the curved surface of the cylinders. The tubes were joined to the cross-shaped common header where one other line went to the gas adsorption pump and the fourth line went to the gas manifold through valve (5) (Fig. 3.1). A photo of the assembled heat switch and its attachment to the heat sink base, plus the cross-shaped common header is shown in Fig. 3.9.

3.2 Pump Fabrication

Figure 3.9 also shows the adsorption pump which was a cylinder machined from a solid piece of copper in accordance to the dimensions shown in Fig. 3.10. There was a continuous copper rod in the form of a hook that was protruding out from the closed end of the cylinder. This rod was later soldered onto the heat link wire leading to the heat sink base of the pump. A 130 Ω heater was wound around the copper cylinder and a silicon diode sensor was attached onto the closed end surface. Charcoal was bonded onto the cylindrical surface by indium and the end cap which had the gas tube was soldered onto the cylinder. The gas tube went to the cross-shaped common header.

3.3 Test Apparatus Fabrication

The pump base was a solid copper cylinder, one end of which became the bottom of the inner surface of the third dewar (Fig. 3.11). Both the inner and the outer surfaces of the dewar were made of stainless steel. The outer surface was supported by a brass fixture which had a neck through which the pump base is allowed to go. The touching of the pump base to the outer surface was prevented by teflon pins. The vacuum jacket between

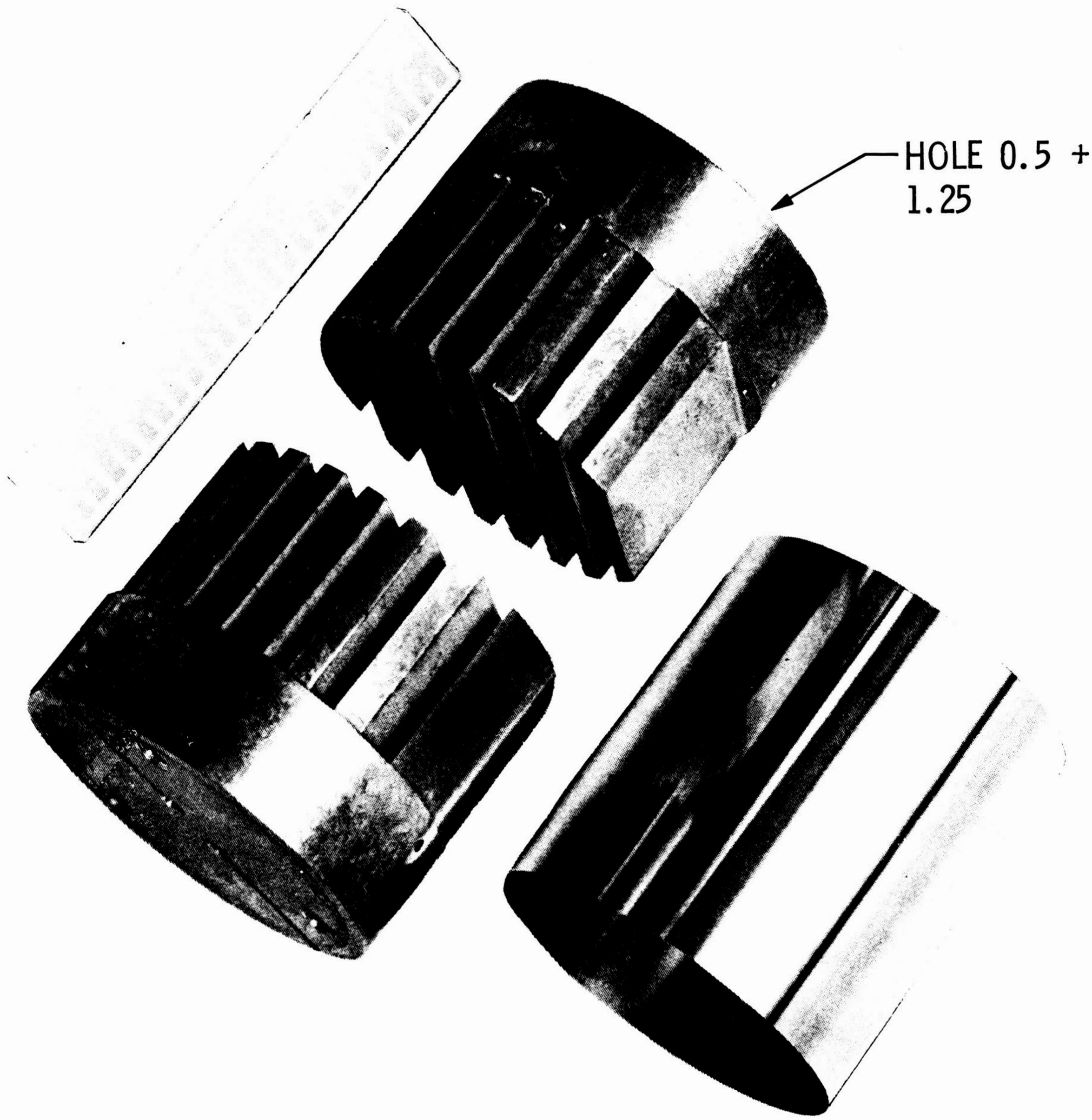

Figure 3.7. Two Copper Finned Heat Switch Cylinders and Stainless Steel Support Tube

(All measurements in inches)

Fig. 3.8. Gaps In-Between Fins when Cylinders Interlocking Together in the Support Tube

Figure 3.9. View of Cross-Shaped Common Header For Gas Flow
Between the Heat Switch and the Adsorption Pump

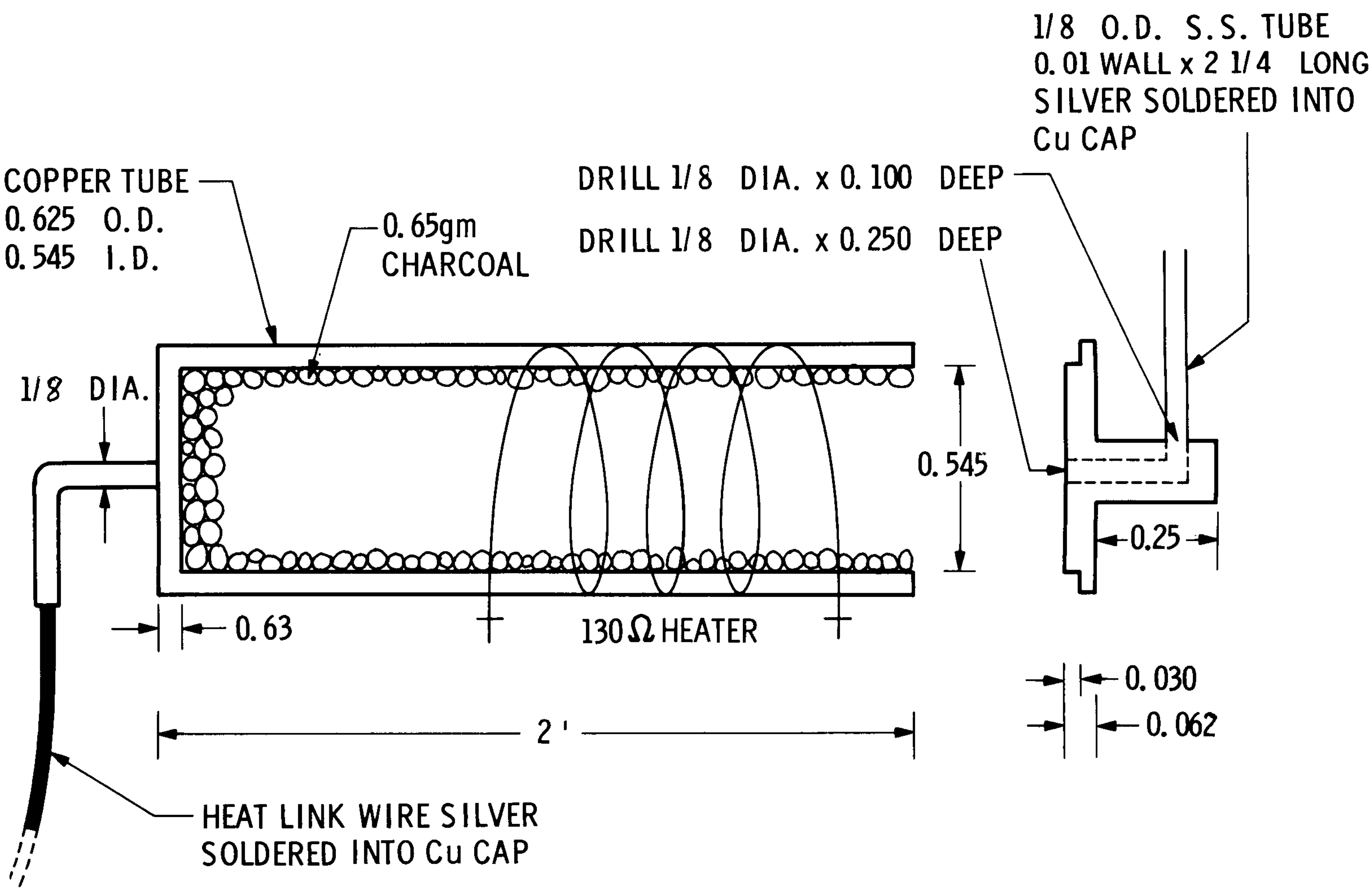

Figure 3.10. Sorption Heat Switch Pump

(All measurements in inches)

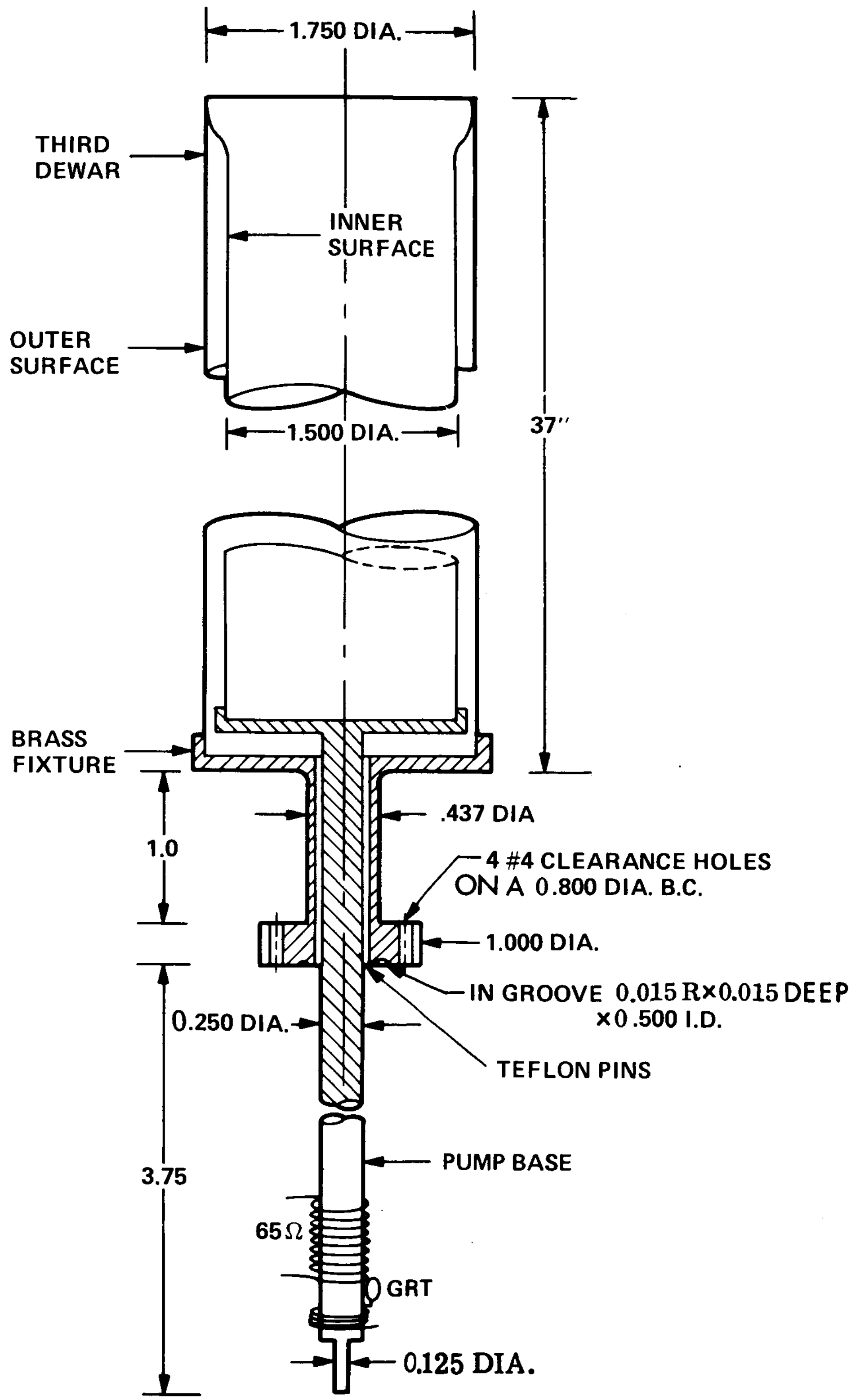

Figure 3.11. Pump Base and the Third Dewar

(All measurements in inches)

the inner and the outer surfaces would be common to the vacuum chamber by attaching the brass neck on to the top plate of the vacuum chamber. There was a heater of 65 Ω and a germanium sensor attached onto the pump base cylinder. A photo of the pump base and its thermal attachment to the pump is shown in Fig. 3.12.

The top plate of the vacuum chamber (Fig. 3.13) was machined from a solid piece of copper with the hole provisions for the attachment of the vacuum vessel and the third dewar. There was a cylindrical neck protruding from the inner side of the plate onto which the cold side of the heat switch would be attached. A heater of 23.2 Ω was wound around the neck for the temperature control of the heat sink base for the heat switch.

The vacuum vessel was constructed from the stainless steel tube (Fig. 3.14). The groove on the flange was for the O-ring joint where the vessel was attached onto the top plate. There was a stainless steel tube connecting the vessel to the evacuating system. The tube also serves a conduit for the electrical wires of the test apparatus (Fig. 3.1). A photo of the third dewar and the stainless steel connecting tube is shown in Fig. 3.15.

3.4 Test Control and Data Acquisition

The objective of the data acquisition system in the present tests was to control and record the temperatures and the energy inputs to the four different regions in the heat switch test apparatus, namely the hot side and the cold side of the heat switch, the adsorption pump, and the pump base. The major hardware in the system is the Hewlett-Packard microcomputer HP-87XM, the Hewlett-Packard Data Acquisition/control unit HP-3497A which provides the functions of scanning 40 channels at the rate of 50 readings per sec, of supplying a current source of 10 μA to 1 mA, of measuring voltage from 0 V to 100 V with 0.001% accuracy, and of converting a digital signal to an analog output from 0 V to ±10 V. These analog outputs (0V to 10 V) which control the amount of voltage coming out from the four programmable power supply units are generated from four digital to analog (D/A) boards. The power supplies #1 and #2 have an amplifier with a gain of four, while power supplies #3 and #4 have a gain of one. The flow chart that shows the interaction among the components is presented in Fig. 3.16.

The brain of the system is the microcomputer where the software program HSCONTROL is installed. The program instructed the HP-3497A to scan the eight channels which consist of voltage measurements of four sensors and four heaters at the four different regions. Before scanning the temperature channel, the program instructs the HP-3497A to send a certain amount of electrical current to each sensor at that region via the HP-3497A Data Acquisition unit. The amount of the current depends on the

Figure 3.12. Thermal Attachment for the Heat Switch and the Adsorption Pump

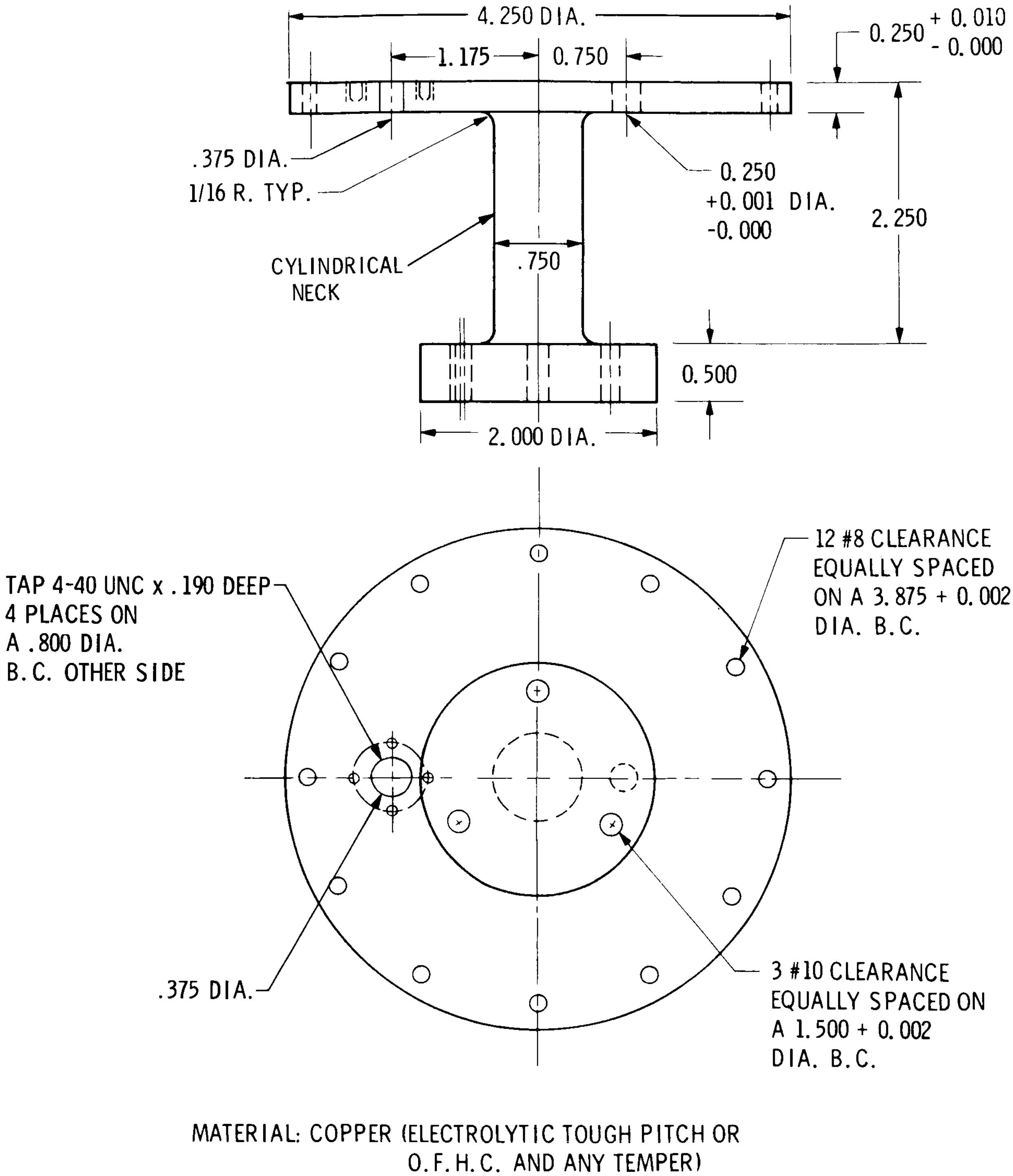

Figure 3.13. Top Plate of the Vacuum Vessel

(All measurements in inches)

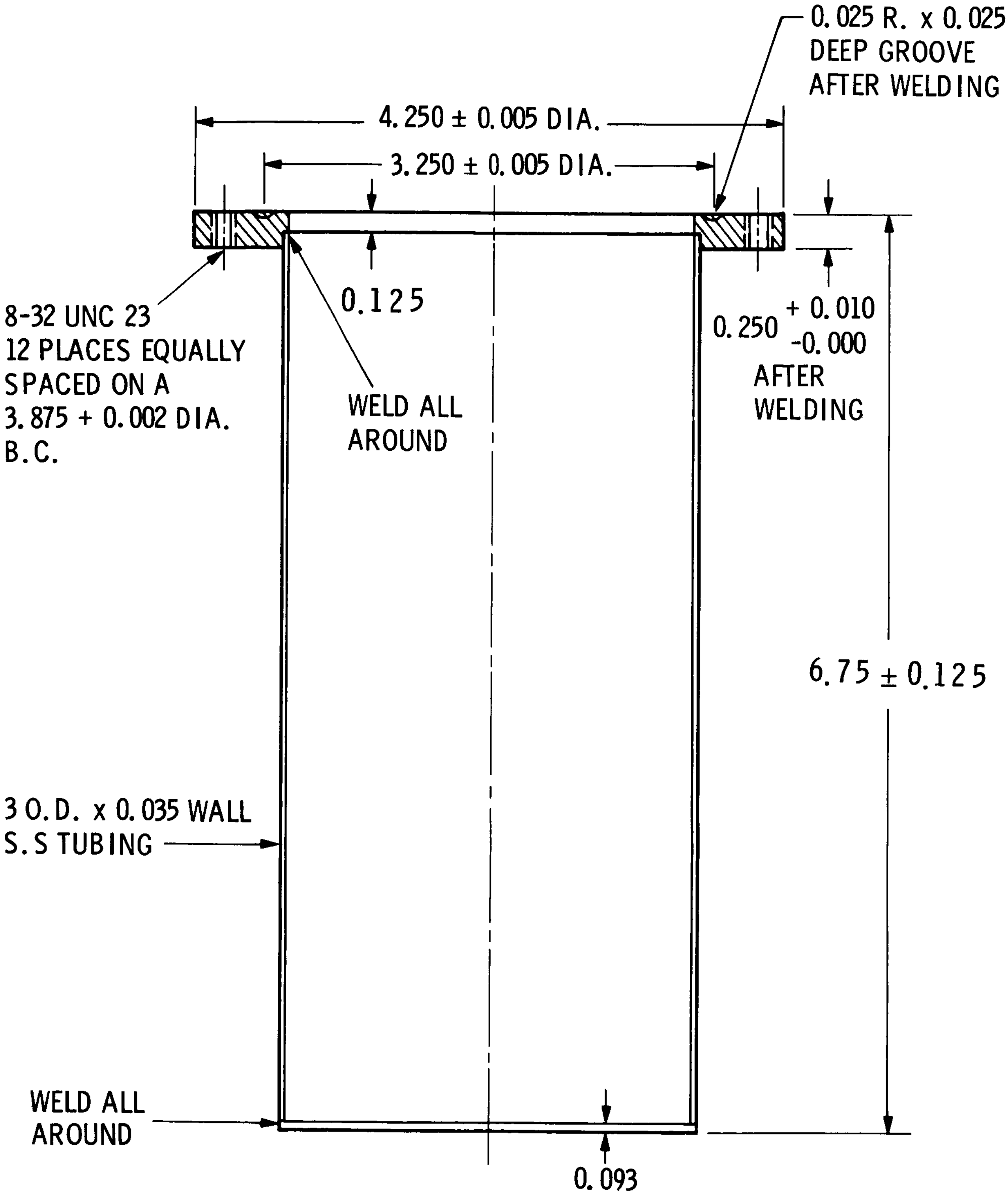

Figure 3.14. Stainless Steel Vacuum Vessel
(All measurements in inches)

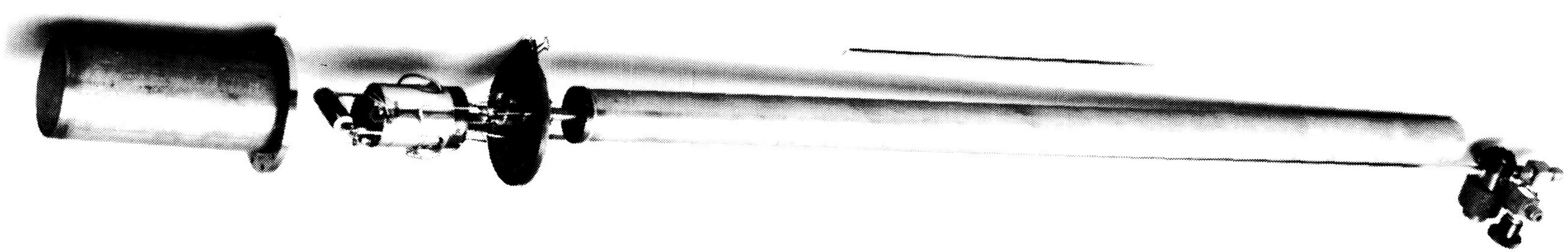

Figure 3.15. The Third Dewar and the Heat Switch Test Apparatus

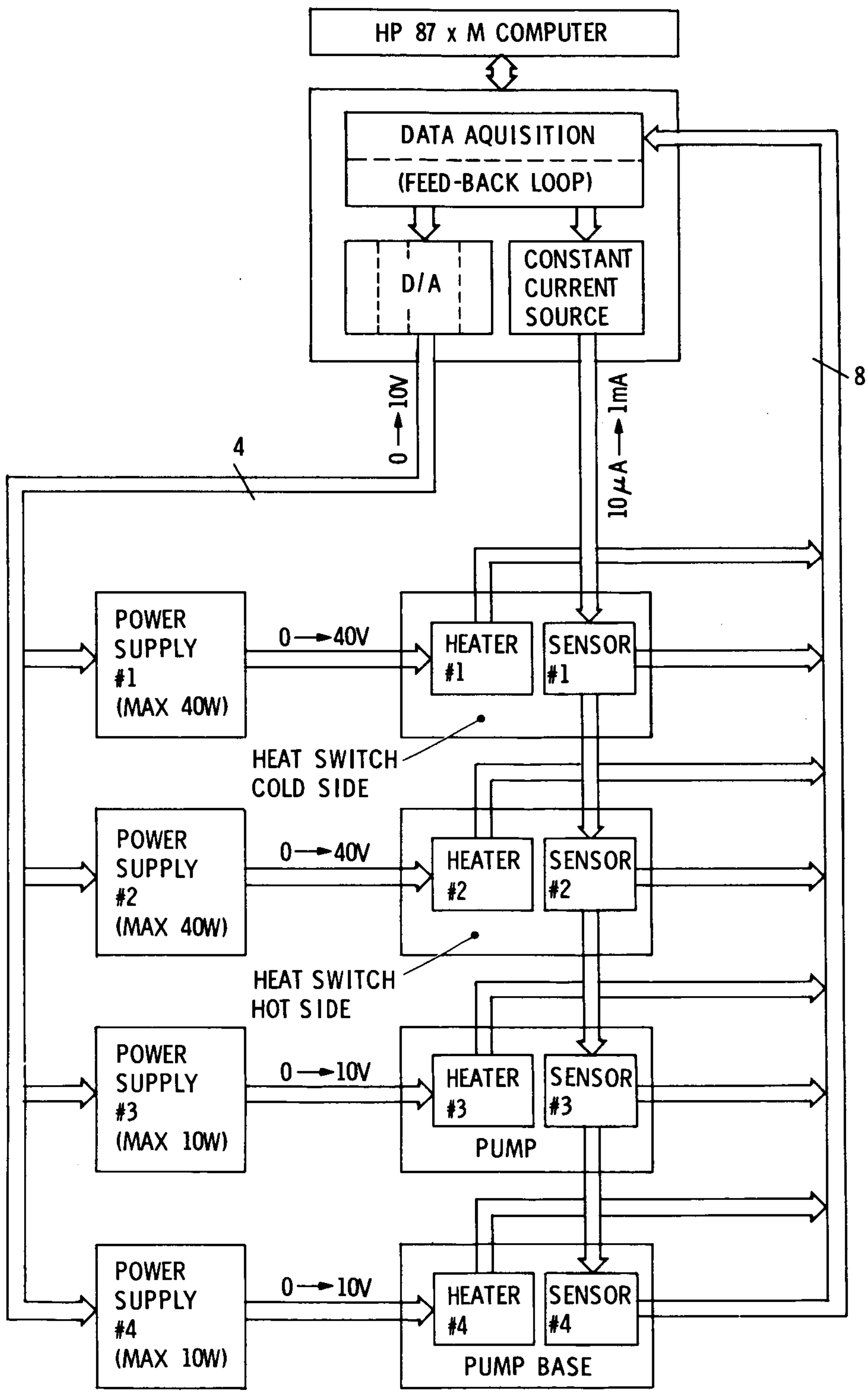

Figure 3.16. Data Acquisition and Temperature Control Feedback

type of the sensor and the temperature range. For a silicon diode sensor the current is 10 μA, and for a germanium sensor the currents are 10 μA, 100 μA, and 1 mA for the temperature ranges of 4 to 10K, 10 to 40K, 40 to 100K, respectively. Then the voltage of that sensor is measured by the voltmeter of HP-3497A and the value is fed back to the HP microcomputer and stored in the memory. A similar procedure takes place to record the voltage supply to each heater. When the scanning is completed, the program calculates the input power Q for each region by

$$Q = V^2/R \tag{3.1}$$

where

V = the input voltage from the power supply
R = the resistance of the heater in each region

The resistance is not a constant but is adjusted each time to compensate for temperature effects at that region. The program also converts the voltage measurement of each sensor to the temperature in degrees kelvin. For the silicon sensor, the conversion is based on the interpolation of a voltage-temperature conversion table, while for the germanium sensor the conversion is based on a polynomial equation. A sample run of HSCONTROL is listed in Appendix C.

A very special feature in this program is the feedback loop which monitors and controls the heaters each few seconds in order to keep the temperature at a particular region at a constant range. The accuracy of the temperature control depends on the type of the computer used and the time interval between two sequential readings. The temperature of the four regions (the hot side, the cold side, the pump, and the pump sink) are compared with the temperatures which were specified at the input phase of the program. If the temperature of a region is higher than the specified final temperature of that region, the subroutine will adjust or turn off the power supply of that region. Otherwise, the power will remain on until the temperature reaches the final value. If the power is off when the temperature drops below the final value, the subroutine will turn the power supply on. This feedback mechanism can control the temperatures within ±0.1 K of the final value.

During the experiment, the user has many options to alter the conditions by using the 14 function keys. For example, by deactivating the feedback loop the user can manipulate the pump and the hot side voltages. However, the user can always override the power supply to the hot side via a special programmed function key on the keyboard. The voltage on the heater can be increased or decreased by an order of 0.1 V or 1V increments. The user can also override all power supplies by terminating the control program. A photo of the Data Acquisition System, together with the heat switch test dewar, is shown in Fig. 3.17.

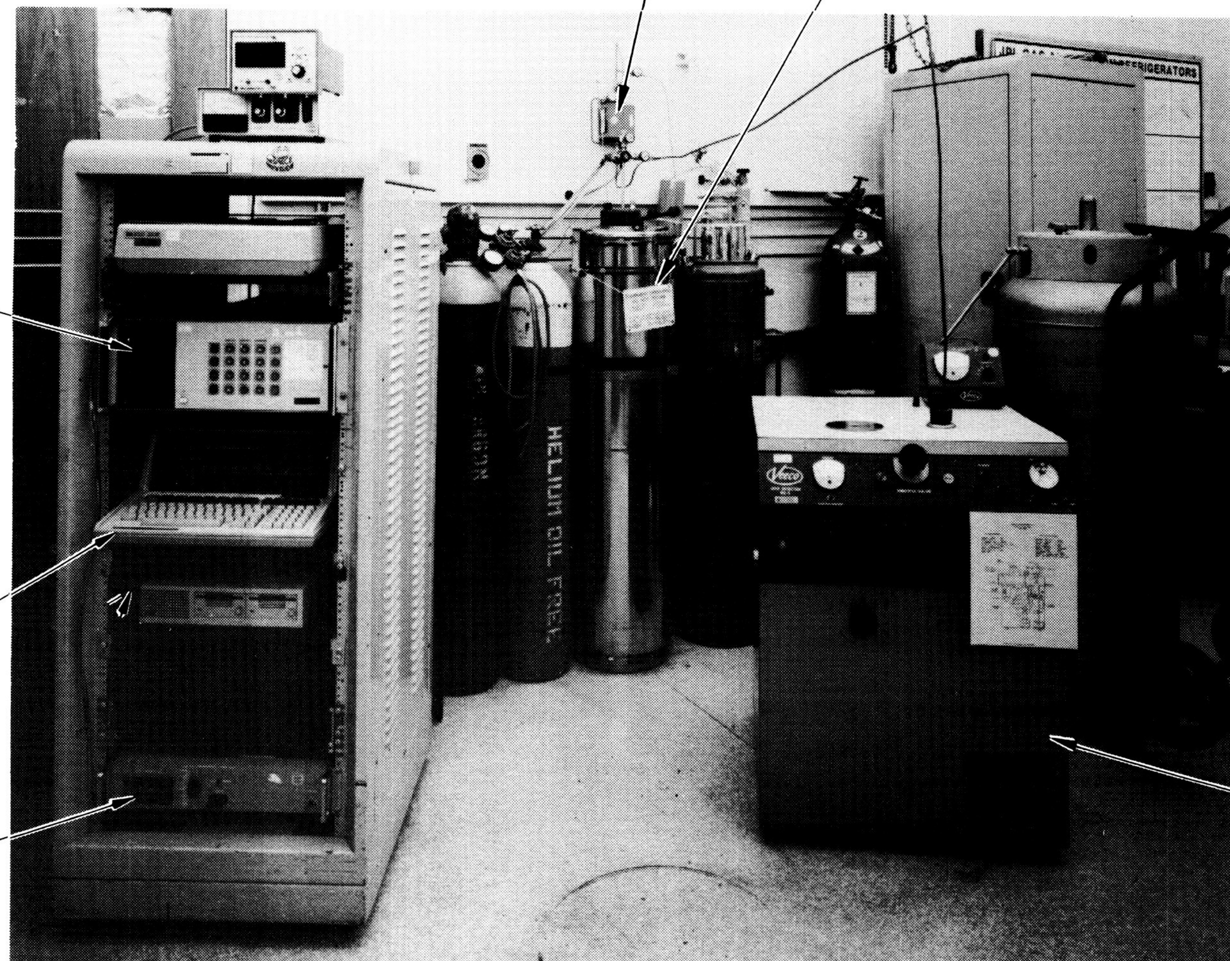

Figure 3.17. Test Facility

c-2

4.0 TEST PROCEDURE AND RESULTS

After the heat switch and the test apparatus were fabricated, a test plan was developed to determine the heat transfer rate from the hot side to the cold side of the heat switch. The first series of tests involved the heat switch with no adsorption pump. The heat transfer rate was determined when the switch was filled with hydrogen gas and when the switch was evacuated. The adsorption pump was then installed and the switch was turned on and off by controlling the pump temperature. The second series of tests involved the adsorption pumps with different gas loading of three different gases (hydrogen, nitrogen, and neon). These first two series of tests were performed when the cold side of the heat switch was thermally grounded to liquid nitrogen (i.e., T_C = 80 K). The third series of tests simulated the operational conditions of the self-actuated heat switch (Fig. 2.25). The pump was cooled to about 10 K during the off mode while the switch temperatures were at 10 K, 20 K and 80 K. Because of the temperature conditions, only helium was used in this series. Error analysis was performed to determine the error bounds of the heat flow and the temperature data. The heat leak of the system was then calculated and it was used to adjust the power input data and, hence, determine the true heat flow through the switch.

4.1 Heat Switch Tests Without Gas Adsorption Pump

In the first series of tests, the heat switch was tested without the adsorption pump. The cold side was attached to the heat sink at liquid nitrogen temperature when the inner dewar was filled with liquid nitrogen (Fig. 3.1). The heat switch was suspended freely in the vacuum chamber so any heat input onto the hot side had to go through the heat switch. Before the test the gas manifold, the heat switch, and all the gas lines were evacuated through valve (1) and the vacuum vessel was evacuated through valve (6) at room temperature to a pressure less than 10^{-5} torr. Liquid nitrogen was put into the outer and the inner dewars. At the time of the tests, the third dewar was not yet installed. When the cold side was cooled to liquid nitrogen temperature, heat was supplied to the hot side of the switch. The heat input Q_H and the temperatures at the hot side T_H and the cold side T_C were recorded until both temperatures reached steady state. The amount of heat supplied was then changed and another set of steady state temperatures was recorded. The procedure was repeated for five to six sets of heat inputs. A plot of the various adjusted heat inputs* Q on

---

* The adjusted heat input, which is the heat input Q_H plus or minus any heat leak from the gas line, will be discussed in Section 4.5.

the hot side versus steady state temperature differences ΔT (i.e., the hot side temperature minus the cold side temperature) is presented in Fig. 4.1. Based on these data, the effective thermal conductance of the heat switch, when no gas was present, was calculated from the gradient of the curve as 5×10^{-3} W/K. Then the gas gap was filled with hydrogen gas of 96 torr, and a similar procedure was taken to obtain the plot of the adjusted heat input Q versus ΔT (Fig. 4.2). The conductance when the heat switch was filled with the hydrogen gas was 5 W/K.

4.2 Heat Switch Tests with Hydrogen, Nitrogen, and Neon

In the second series of tests, the adsorption pump was installed and tests were performed for three different gases which included hydrogen, nitrogen, and neon in the heat switch at 80 K. The tests also examined the effects of gas loading on the heat switch performance. Before the test the gas manifold, the heat switch, the adsorption pump, and all the gas lines (Fig. 3.1) were evacuated through valve (1) and the vacuum vessel was evacuated through valve (6). With valves (2) and (5) closed, a quantity of gas was introduced into the gas manifold through valve (4). This amount of gas was measured by the differential pressure transducer with valve (3) open. This is the initial gas pressure in the manifold. Valve (3) was then closed and valve (5) was opened to allow the gas to be adsorbed by the adsorption pump. Valve (5) was then closed and the residue pressure in the manifold was measured by opening valve (B). The test was ready to start.

Both the cold side of the heat sink and the pump base were thermally grounded to liquid nitrogen. When the heat switch and the pump reached the equilibrium temperature, the experimental procedure was taken to obtain a set of the steady state temperature differences (T_H - T_C) for a given set of heat inputs Q_H on the hot side when the switch was off. The heater on the adsorption pump was then turned on and this kept the pump temperature above the heat sink temperature. The heating of the charcoal inside the pump liberated the gas to the gap and turned the switch on. Heat was then supplied to the hot side of the switch. The procedure was repeated for a new set of inputs Q_H and temperatures T_H and T_C.

The system was then evacuated. A different quantity or type of gas was loaded into the heat switch. Table 4.1 summarizes the results of these preliminary tests which involved hydrogen, nitrogen, and neon at different gas loading pressures. The effective thermal conductance of the heat switch during the off mode and the on mode was calculated from the gradient of the curve of Q versus T_H - T_C. The switch ratio was then computed by

$$\text{Switch Ratio} = K_{ON}/K_{OFF} \qquad (4.1)$$

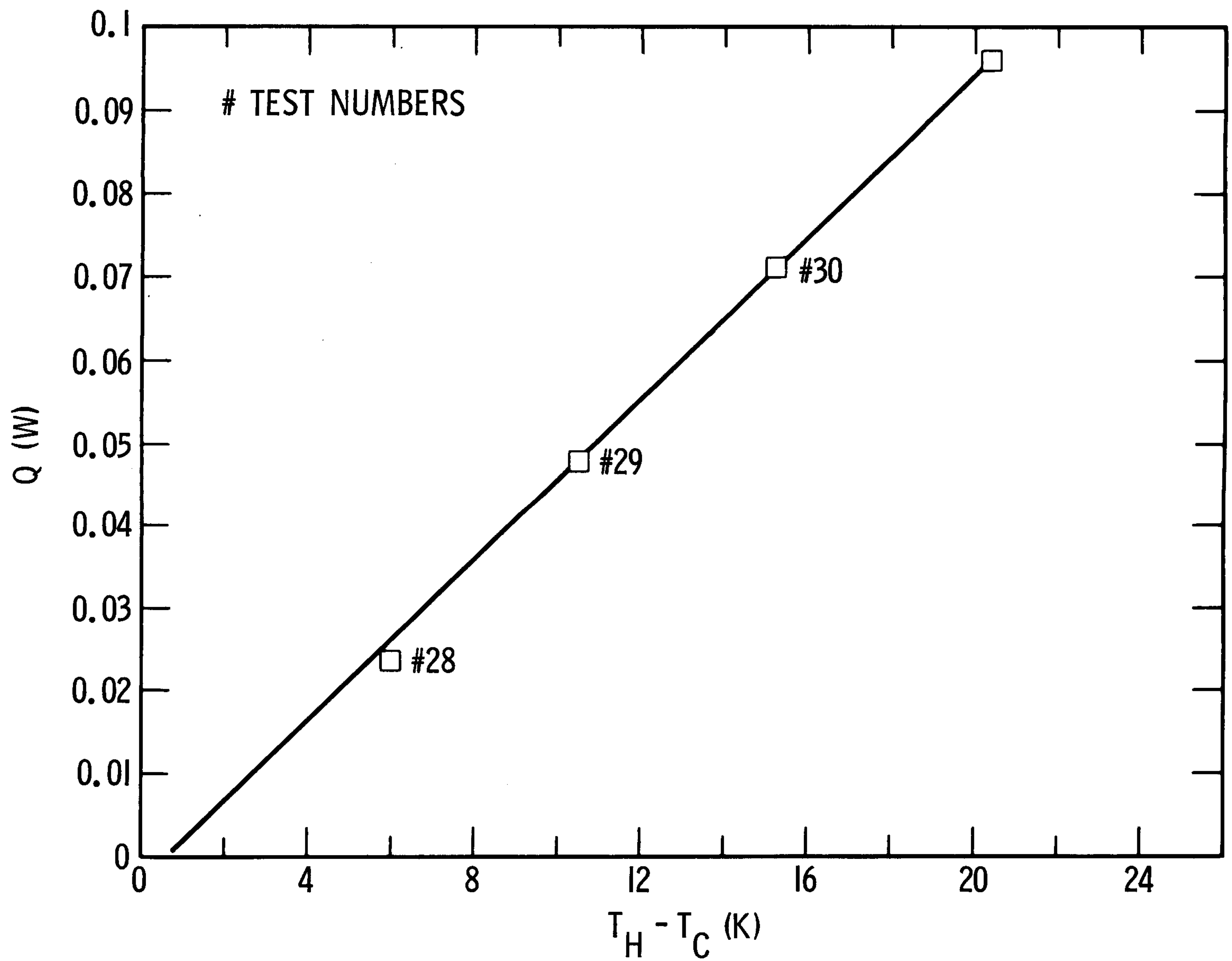

Figure 4.1. Heat Switch Test With No Pump and With No Gas

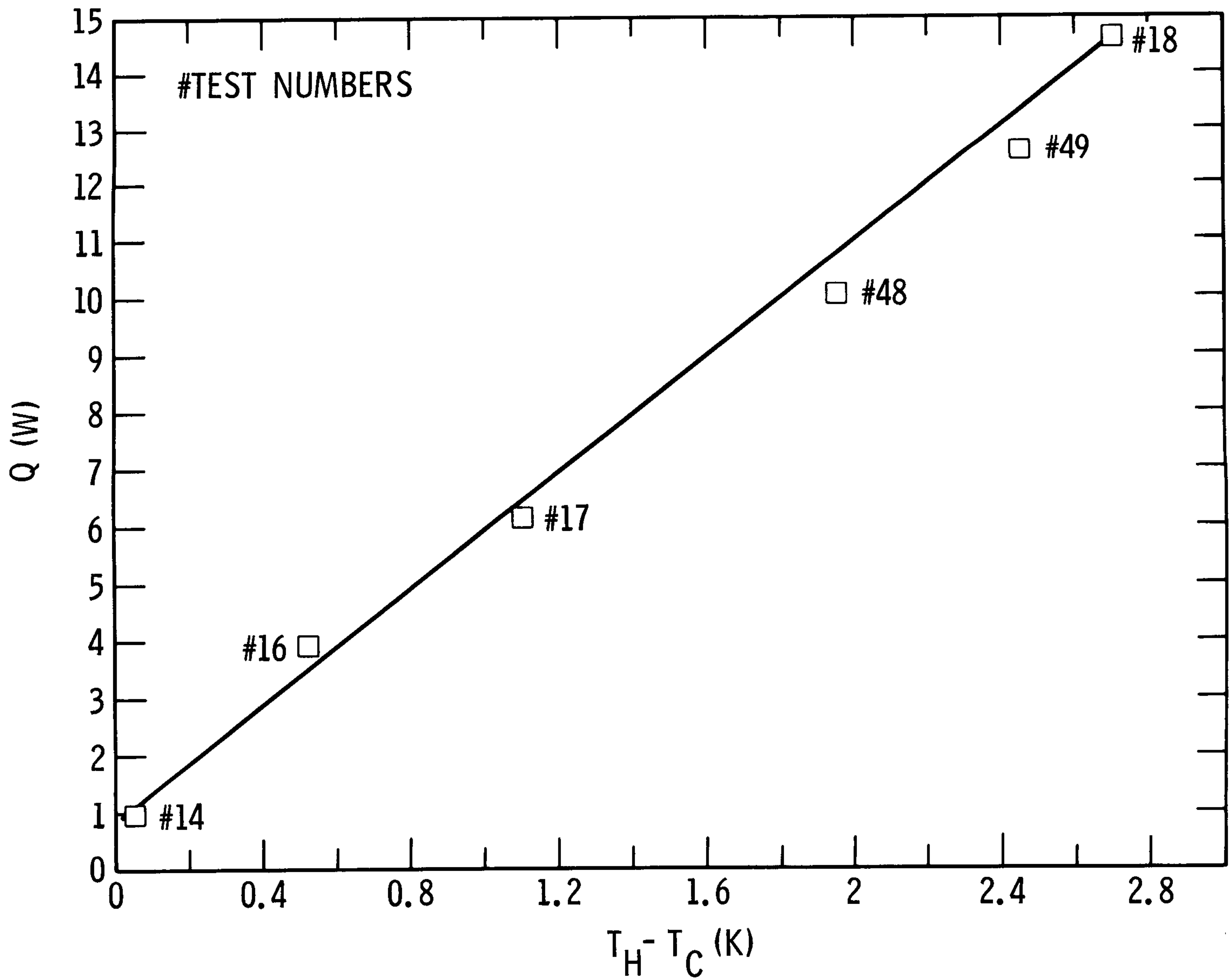

Figure 4.2. Heat Switch Test With Pump and 95 torr of Hydrogen Gas

Table 4.1. Heat Switch Test for Different Gases With Different Gas Loads

Gas Type	Initial Pressure Torr	Final Pressure Torr	Off Mode			On Mode			Switch Ratio
			Exp#	Pump Temperature (K)	Conductance K (W/K)	Exp #	Pump Temp.	Conductance K (W/K)	
H_2	10.01	3.75	37	78.64	0.051	38	233.74	5.021	98.45
	5.16	1.83	41	78.61	0.026	42	179.57	3.906	150.23
	2.5	0.89	44	78.84	0.0149	45	209.96	3.390	242.13
	1.32	0.54	46	78.58	0.00973	47	209.87	3.681	275.49
N_2	2.58	0.65	50	78.64	0.00501	51	319.27	1.025	200.98
	6.03	1.90	52	78.83	0.00475	53	319.53	1.206	253.848
Ne	2.52	1.16	54	78.17	0.382	54	245.0	1.697	4.44
	1.22	0.52	55	78.28	0.182	55	242.9	1.111	6.11

Among the three gases, neon had the worst heat switch performance when the pump was at 78 K. Even nitrogen which has a boiling point close to 80 K has a switch ratio of only about 200. This is probably due to the fact that the thermal conductivity of nitrogen is relatively poor and that affects the on conductance. The off conductance for nitrogen is 5×10^{-3} W/K which is close to the limit. The charcoal appears to be able to pull the pressure below the radiation limit during the off mode for the nitrogen case. The on conductance for the hydrogen case is close to 5 W/K, but the off conductance is much higher than the radiation limit (5×10^{-3} W/K).

4.3 Heat Switch Tests With Helium

This series of tests involved helium gas when the pump was cooled to about 10 K during the off mode, and when the switch temperatures were at about 10 K, 20 K, and 80 K. These conditions were close to those that would exist in the actual system as discussed in Section 2.5. During the tests, the third dewar for the pump base (Fig. 3.1) was filled with liquid helium. With the operation of the pump base heater, the pump base temperature could be maintained in the 10 K range. Hence, the heat switch pump could be at 10 K, while the cold side of the heat switch could be at 10 K, 20 K, or 80 K if appropriate cyrogen was put into the inner dewar and the heater on the cold side was turned on. For the 10 K and the 20 K test series liquid helium was put into the inner dewar, while for the 80 K test, liquid nitrogen was used.

The test procedure for the helium test was similar to that for the hydrogen as described in the previous Section. The heat switch was first evacuated and a measured quantity of helium was put into the adsorption pump. When all the temperatures reached equilibrium, heat was supplied to the hot side of the switch. The input Q_H and the temperatures at the hot side T_H and the cold side T_C were recorded until both temperatures reached steady state. The heat supplied was then changed and another set of steady state temperatures was recorded. The procedure was repeated for five to six sets of heat inputs when the switch was off. A plot of the various heat inputs Q_H on the hot side versus the steady state temperature difference ΔT is presented in Figs. 4.3, 4.4, and 4.5 for the temperature range of 10 K, 20 K, and 80 K. These curves are close to straight lines, but they do not go to the origin point at $\Delta T = 0$. After taking into account the heat leak at the heat switch due to the cross-shaped common header, the actual amount of heat Q that flows through the switch can be computed. These Q values are also plotted on Figs. 4.3, 4.4, and 4.5 and these curves go through the point of origin. Based on these data, the effective thermal conductance of the heat switch during the off mode is calculated from the slope of the straight line curves, i.e.,

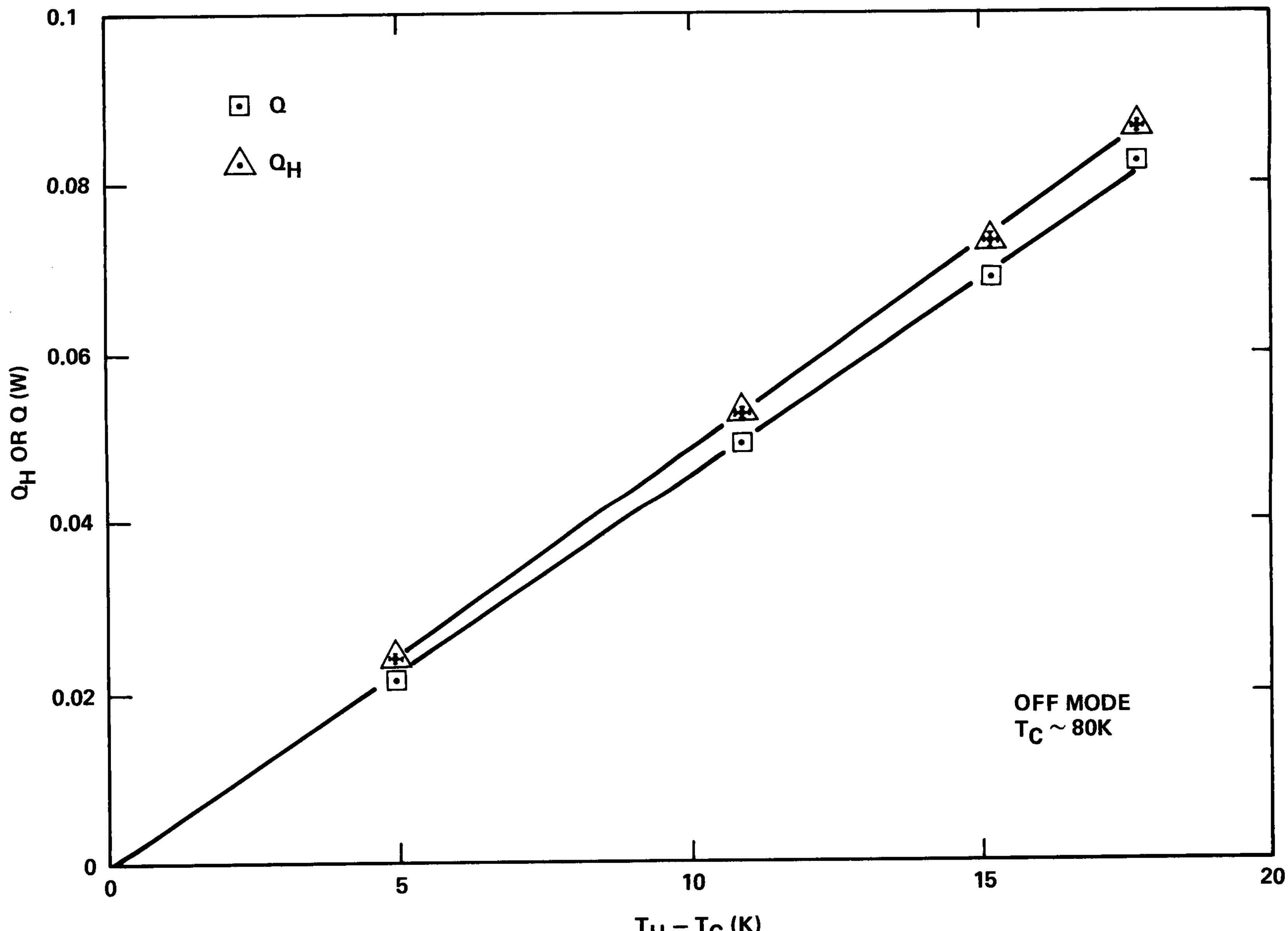

Fig. 4.3. Heat Input Q_H and Heat Flow Q During the Off mode of the Heat Switch at 80K Versus Temperature Difference Across the Switch

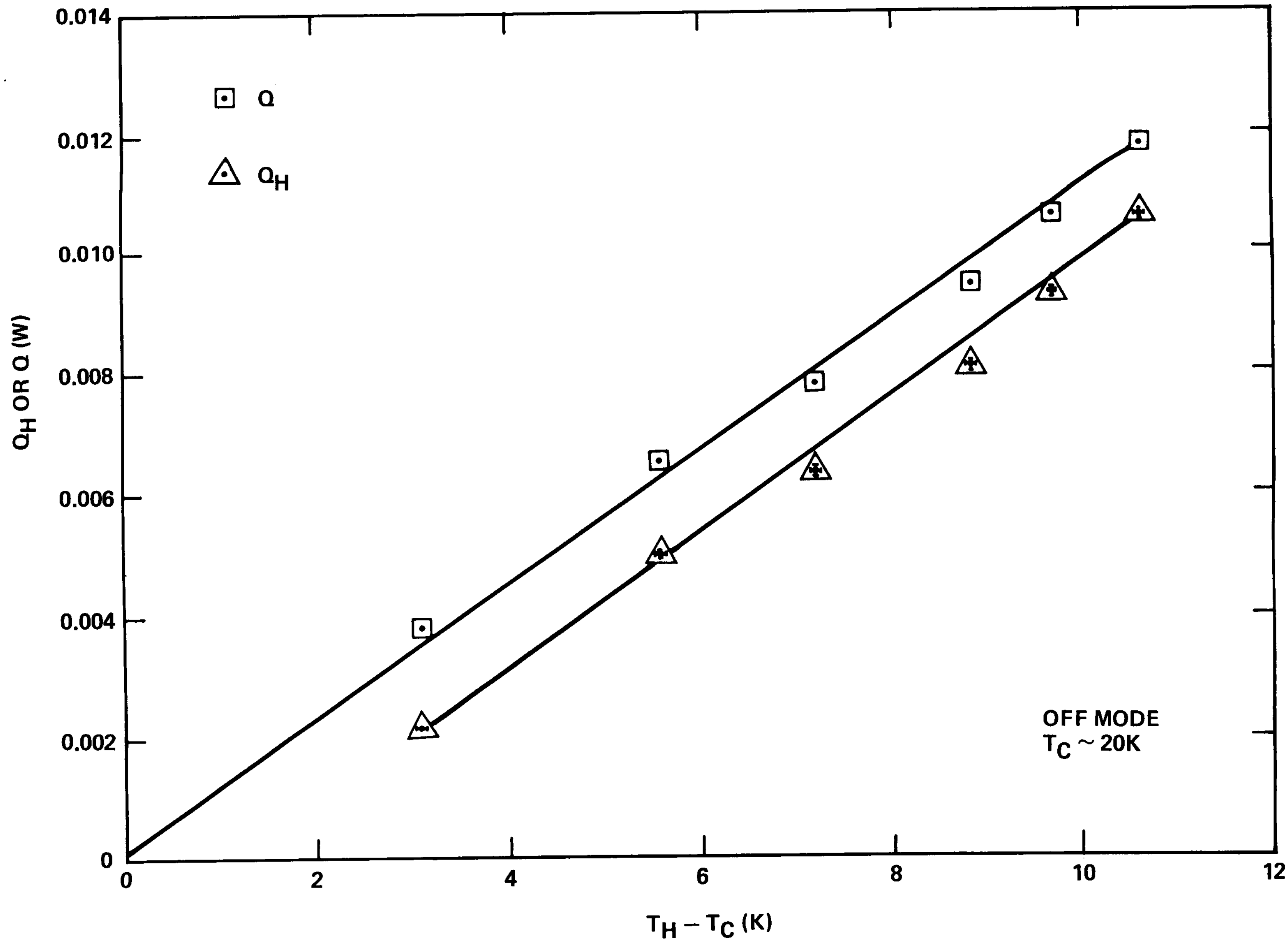

Fig. 4.4. Heat Input Q_H and Heat Flow Q During the Off mode of the Heat Switch at 20K Versus Temperature Difference Across the Switch

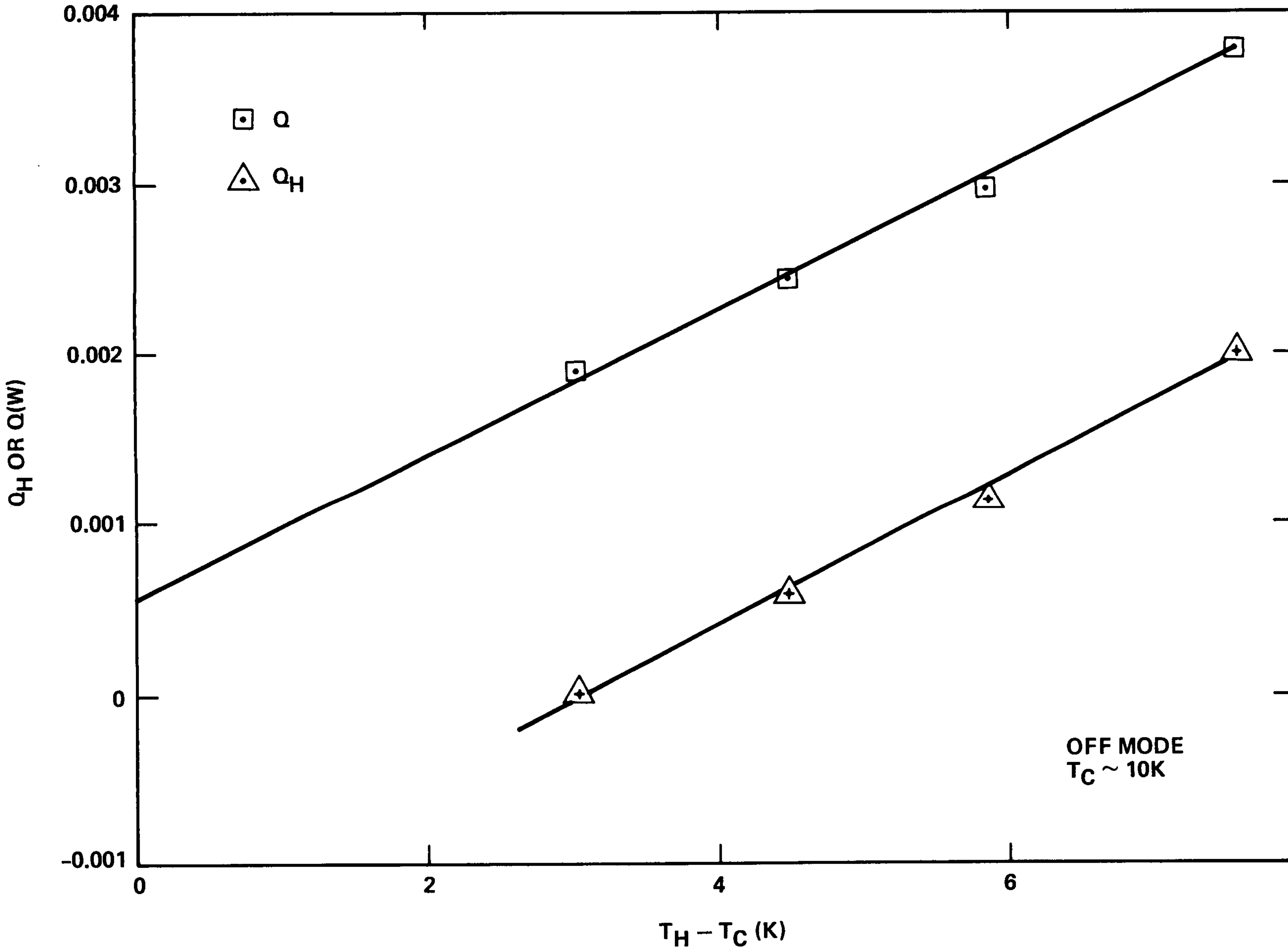

Fig. 4.5. Heat Input Q_H and Heat Flow Q During the Off mode of the Heat Switch at 10K Versus Temperature Difference Across the Switch

$$K_{OFF} = Q/\Delta T \tag{4.2}$$

The cross lines at the data point represent the magnitude of the error bounds which will be discussed in the next Section. The heat flow versus the steady state temperature difference (ΔT) when the pump was on is presented in Fig. 4.4. These curves are not straight lines. The effective thermal conductance of the heat switch during the on mode is calculated from the gradient of the curves at T = 10 K, 20 K, and 78 K, i.e.,

$$K_{OFF} = dQ/d(\Delta T) \tag{4.3}$$

The error bounds of the data are also shown in these three Figures.

The switch ratio S.R. is then computed by

$$S.R. = K_{ON}/K_{OFF} \tag{4.4}$$

The numerical values of the on conductance, the off conductance and the switch ratio for these temperature ranges are summarized in Table 4.2. A more thorough data presentation will be found in Section 5 when data are to be compared with the analytical results.

4.4 Error Analysis

A series of tests and calculations was performed to estimate the systematic errors which are reproducible inaccuracies introduced by the equipment and calibrations. The accuracies of the temperature readings and the power input on to the heat switch are the main concerns of this error analysis.

The following equations are used to calculate the error bounds from the three standard forms of equations [4.1]:

For addition and subtraction, such as

$$x = au + bv \tag{4.5}$$

then $\sigma^2{}_x = a^2\sigma_u{}^2 + b^2\sigma_v{}^2$ (4.6)

For multiplication and division, such as

$$x = + auv \tag{4.7}$$

then $\sigma_x 2/x^2 = \sigma_u 2/u^2 + \sigma_v{}^2/v^2$ (4.8)

For power functions such as

$$x = au^{+b} \tag{4.9}$$

then $\sigma_x/x = b\ \sigma_u/u$ (4.10)

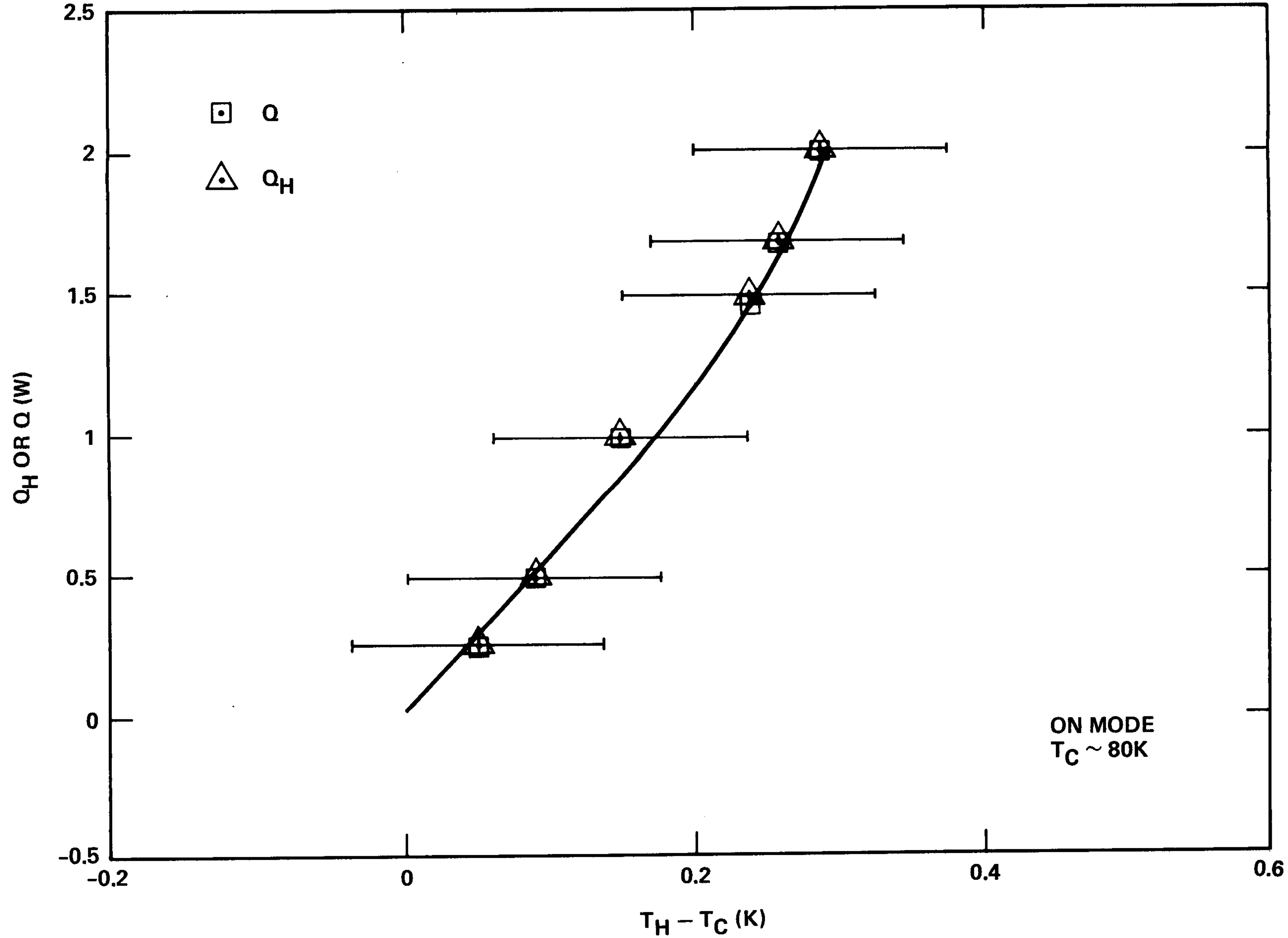

Fig. 4.6. Heat Input Q_H and Heat Flow Q During the On mode of the Heat Switch at 80K Versus Temperature Difference Across the Switch

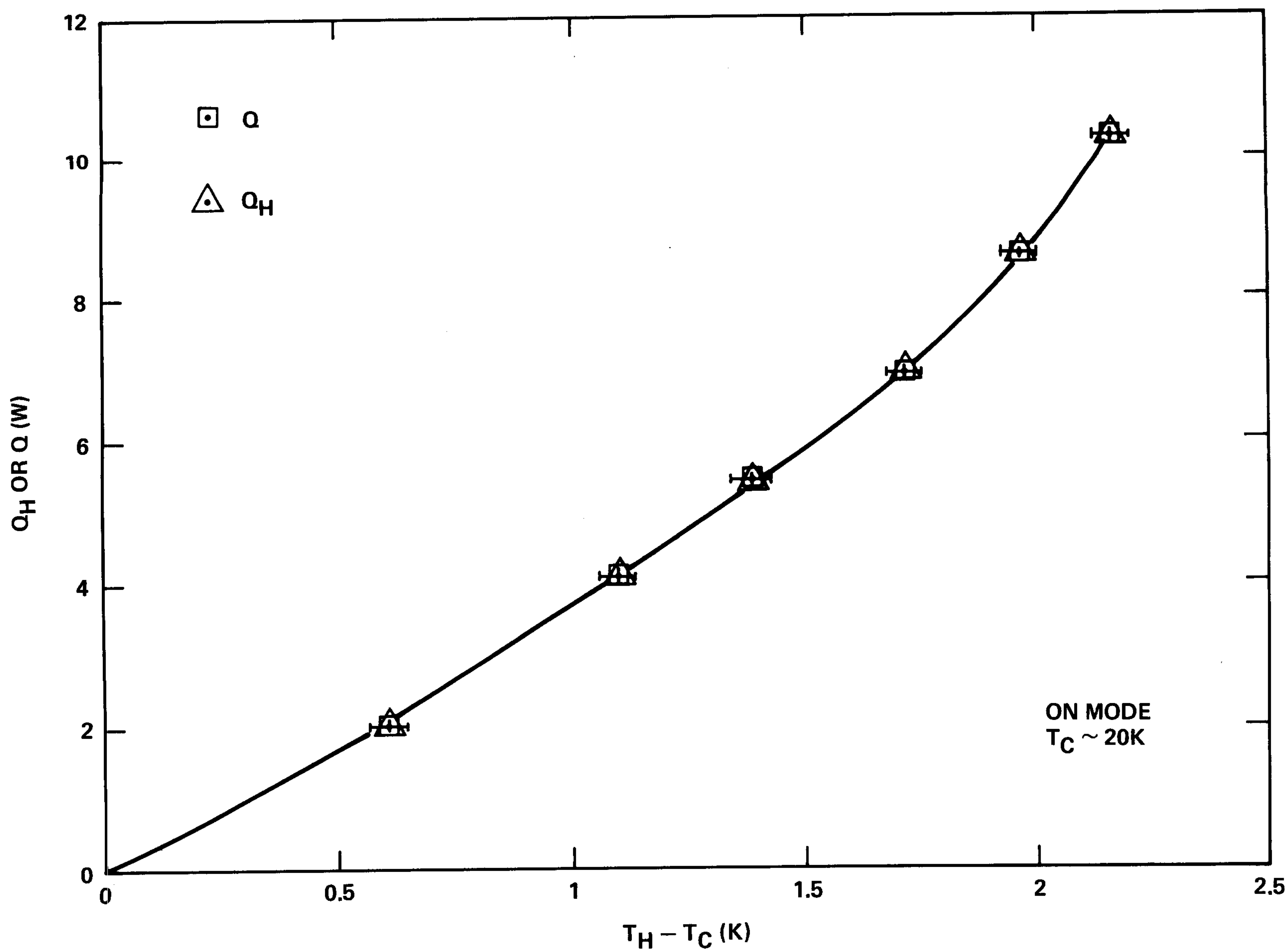

Fig. 4.7. Heat Input Q_H and Heat Flow Q During the On mode of the Heat Switch at 20K Versus Temperature Difference Across the Switch

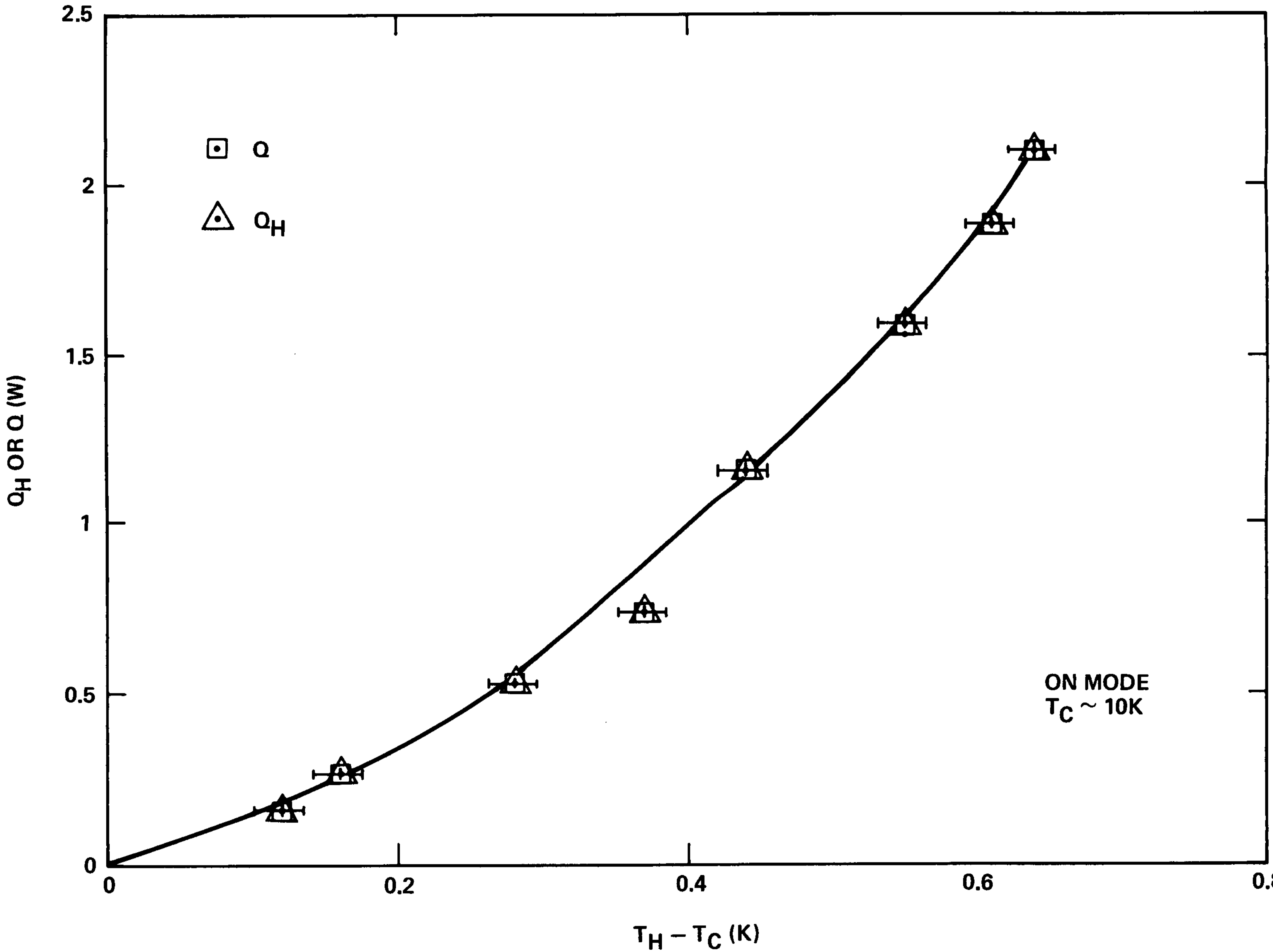

Fig. 4.8. Heat Input Q_H and Heat Flow Q During the On mode of the Heat Switch at 10K Versus Temperature Difference Across the Switch

Table 4.2.
Experimental Data of the On Conductance, Off Conductance, and Switch Ratio of the Straight Fins Heat Switch

Temperature	On Conductance (W/K)	Off Conductance (W/K)	Switch Ratio
10 K	4.9	4.50E-4	10900
20 K	8	1.07E-3	7500
80 K	11	4.90E-3	2245

where x is the dependent variable, a and b are positive constants, and the parameters u and v are dependent variables.

Power

The heat input onto the heat switch Q_H is

$$Q_H = (V/(R_W + R_H))^2 R_H \tag{4.11}$$

where

V = the measured voltage, in volts
R_H = the resistance of the Dale resistor, ohms
R_W = the resistance of the leads from the power supply to the resistor, ohms

The voltage applied to the heat switch was measured by using a HP-3497A Data Acquisition unit with a calibrated accuracy of +3 x 10^{-4} volts. Thus, the error bound for the voltage measurement is

$$\sigma_V = + 3 \times 10^{-4} \text{ volt} \tag{4.12}$$

The heater on the hot side of the heat switch consists of two Dale resistors connected in series. Each has a resistance of about 50 ohms. The total resistance R_T is $R_H + R_W$ where R_H is the resistance of the Dale resistors and R_W is the resistance of the lead wires. The change of the resistance with temperatures was found by applying 1 mA of current to the resistors. The voltage was recorded as the resistor was cooled from room temperature down to 4 K. The resistance R_T was then calculated by

$$R_T = V/I \tag{4.13}$$

where

V = voltage, volt
I = current, amp

The resistance as a function of the temperature was shown in Fig. 3.10. The error bounds for the ampmeter σ_I and the voltmeter σ_V are

$$\sigma_I = +3 \times 10^{-8} \text{ amp} \tag{4.14}$$

$$\sigma_V = +3 \times 10^{-4} \text{ volt} \tag{4.15}$$

The error bound for the resistance was calculated to be

$$\sigma_{RT} = +0.3\ \Omega \tag{4.16}$$

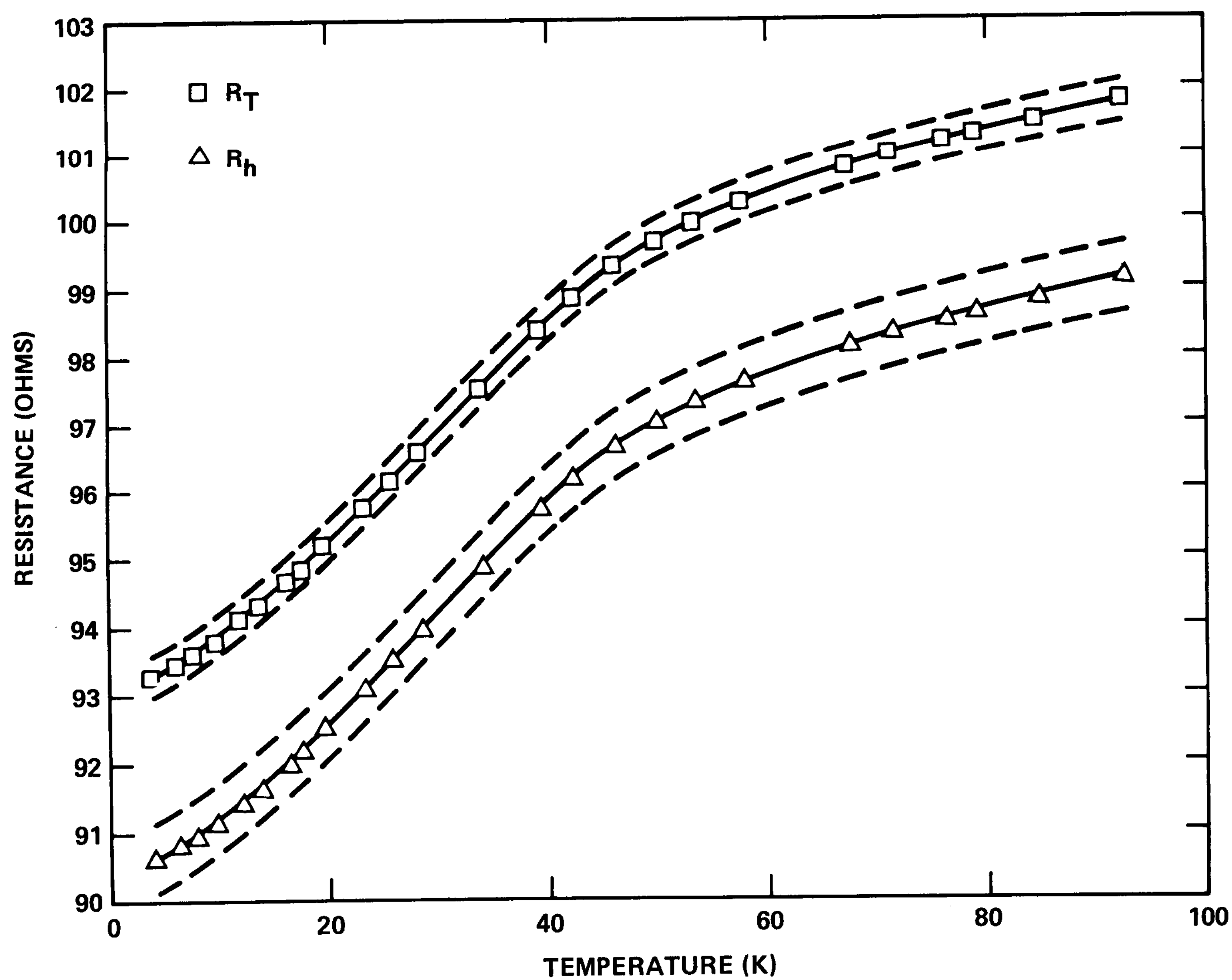

Fig. 4.9. Electrical Resistance as Functions of Temperatures

The resistance of the lead wires changes from 2.60 ohms to 2.69 ohms when the temperature changes from 77.1 K to 4.1 K, respectively. In view of this small change, a mean value of 2.645 ohms was used for R_W to be subtracted from R_T to yield the R_H (Fig. 4.9). Because of the subtraction, the error bound for R_H is

$$\sigma_{RH} = + 0.52 \text{ ohms}$$

With the knowledge of σ_V, σ_{RT}, and σ_{RH}, the error bound for the power input σ_{QH} can be computed. The numerical values for the three temperature ranges are:

T	=	10 K	20 K	80 K
σ_{QH}/Q_H	=	+0.0074	+0.0072	+0.0067

Temperature

The error bound of the Ge sensor at 77 K and the 4 K were found by thermally grounding the heat switch to the liquid nitrogen and the liquid helium baths, respectively. The temperatures of both the hot side T_H and the cold side T_C of the heat switch were recorded. These temperatures were compared to the saturation temperatures at atmospheric pressure. The deviations were noted to be +0.05 K for the sensor on the hot side, and -0.04 K for the sensor on the cold side at 77 K. The deviation is defined as

$$\text{Deviation} = \text{Sensor Temperature} - \text{Saturation Temperature} \quad (4.17)$$

The deviations are +0.014 K and +0.004 K for T_H and T_C at 4 K, respectively.

At 20 K, the error bound is quite different due to the low current used for the measurements. During the experiment, 10 uA was used instead of 100 uA. Hence, one significant digit of the voltage was lost. During the conversion from voltage to degrees kelvin, an uncertainty of +0.116 K was introduced.

The error bounds for the temperature difference

$$\Delta T = T_H - T_C \quad (4.18)$$

are then computed for the temperature ranges

T	=	10 K	20 K	80 K	
σ_{TH}	=	+0.016 K	+0.027 K	+0.077 K	(4.19)
σ_{TC}	=	+0.008 K	+0.026 K	+0.04 K	(4.20)
$\sigma_{\Delta T}$	=	+0.018 K	+0.038 K	+0.087 K	(4.21)

These error bounds σ_{QH}, $\sigma_{\Delta T}$ were used in Figs. 4.4 to 4.8.

4.5 Heat Leak Determination

Due to the arrangement of the gas lines at the cold side and the hot side of the heat switch (Fig. 4.9), a small quantity of heat could leak from the pump and the 300 K room temperature to the heat switch. That would affect the temperature measurement and the heat flow from the hot side to the cold side. To determine the quantity of that heat leak, a thermal circuit (Fig. 4.1) was used. In the model, T_H and T_C represent the temperature nodal points of the hot side and the cold side, respectively. The temperature at the cross-shaped header is T_J, while T_P and T_S are the temperatures of the pump and the pump base, respectively. The thermal resistances between these temperature nodal points are R_K between T_H and T_C, R_1 between T_H and T_J, R_4 between T_J and T_C, R_2 between T_J and T_P, and R_3 between 300 K and T_J. The resistance of the thermal link at the pump is R_5 and R_K is the reciprocal of the K_{ON}, and the K_{OFF} depending whether the switch is on or off. All the gas line resistances R_1, R_2, R_3 and R_4 are calculated by the formula

$$R_k = L_k/(k_k A_k) \text{ when the switch is off} \qquad (4.11)$$
$$= L_k/(k_k A_k + k_g A_{ck}) \text{ when the switch is on} \qquad (4.12)$$

where

L_k = length of the gas line between two nodal points, cm
A_k = stainless steel cross-sectional area, cm^2
k_k = tube thermal conductivity, function of temperature, W/cmK
A_{ck} = cross-sectional area of the gas phase, cm^2
k_g = thermal conductivity of the gas, W/cmK

Since T_H, T_C, and T_P are known from the measurements, T_J could be determined by making a heat flow balance at T_J. Then the adjusted heat Q_{LP} away from the hot side is given by

$$Q_{LP} = (T_H - T_J)/R_1 \qquad (4.13$$

The numerical value of Q_{LP} can be positive or negative depending on the relative values of T_J and T_H, so the true heat flow Q through the heat switch would be

$$Q = Q_H - Q_{LP} \qquad (4.14)$$

where Q_H is the measured heat input onto the hot side.

These are the Q and Q_H which are being reported in this Section.

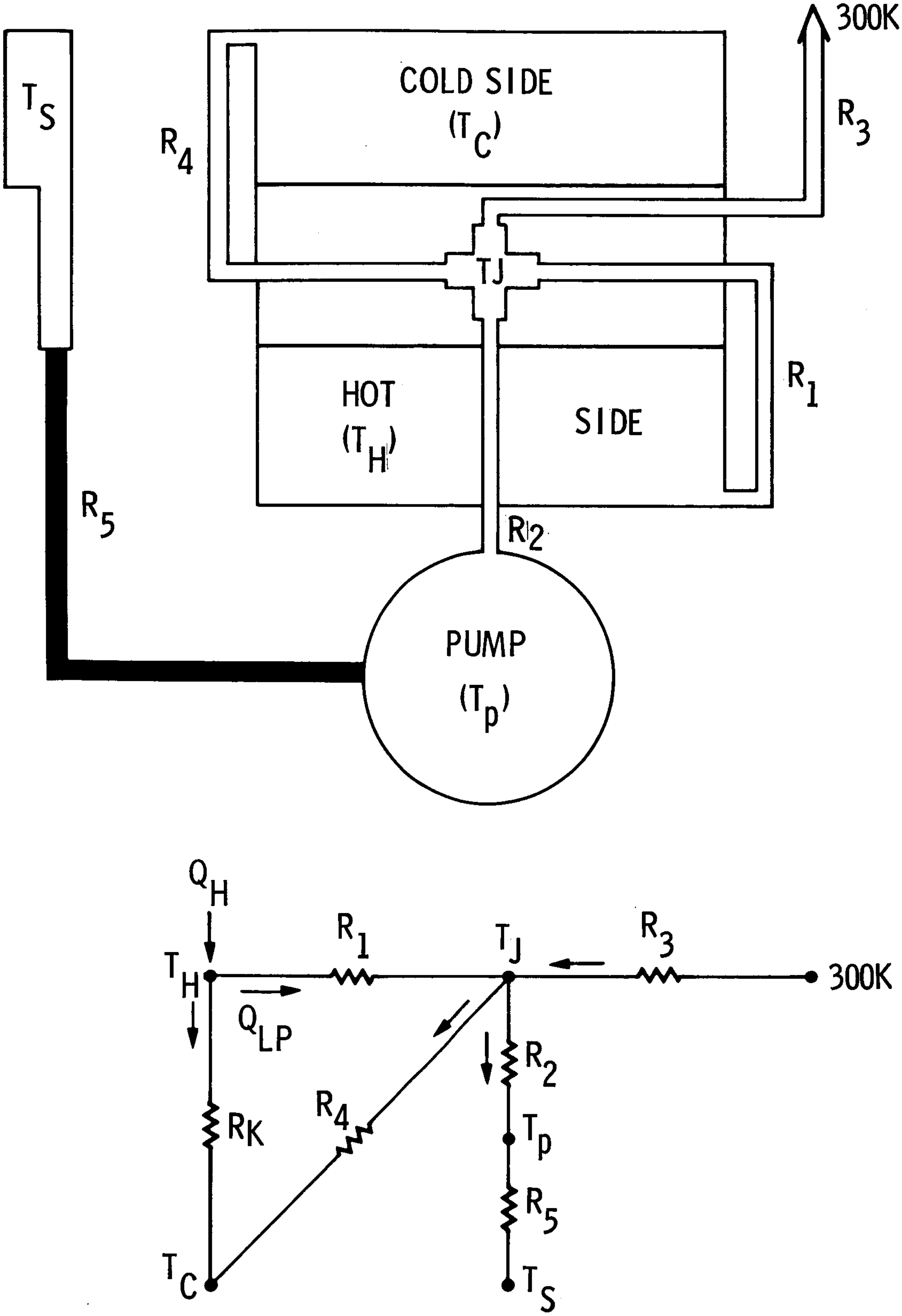

Figure 4.10. Model and Thermal Circuit for Heat Leak Determination

5.0 ANALYTICAL MODEL

As discussed in Section 2, the heat transfer mechanism inside the heat switch is a complicated process. Consider the pair of the fins as shown in Fig. 5.1. When the temperature at the base of the hot side is higher than the temperature at the base of the cold side, heat is first conducted along the fins on the hot side. It is then transferred across the gap by radiation and gas conduction and conducted along the fins towards the base of the cold side. At the same time, heat is conducted from the hot side to the cold side directly through the support tube. Heat is transferred by conduction and radiation across the gaps between the fin tip and the fin base and between the fins and the support tube. In this Section and the thermal network approach in Section 2.0, the heat transfer between the fins and through the support tube was considered. That probably accounts for 70% of the total heat transfer during the on mode and 75% during the off mode. In Section 2.0, the conduction and the radiation across the gap were decoupled and superimposed on each other. The analytical model, described in this Section, will consider the interaction between the conduction and the radiation at the gap and, hence, yield a more precise description of the heat transfer process. A closed-form solution is desirable because it gives a physical insight of the design parameters of the fins, such as the fin dimensions, surface emissivities, etc. This will be extremely useful in design optimization.

5.1 Physical Model

The basic physical model for the analysis involves a pair of the hot fins and the cold fins (Fig. 5.2). The width of the fin D cm, depends on the location of the fin as shown in Fig. 5.1. Both the length L and the thickness 2w of the fin do not change. In Fig. 5.2, the length coordinate is taken as having its origin at the base of the cold side and is positive in the direction toward the fin tip, so the base of the hot side is at x = L. Because the fins are thin and made of highly conductive material, the temperature differences in the thin direction are negligible. Hence, the temperature in the fin is uniformly distributed in the thin direction, and it is a function of x only. Considering a differential element which has a length dx, width D, and thickness w, so the cross sectional A which is nominal to the path of the heat flow is

$$A = wD \tag{5.1}$$

For the hot fin, the energy enters through the cross-sectional area at x + dx of the element by conduction $q_{1,x+dx}$. It leaves by conduction at x and by gaseous conduction, as well as by thermal radiation to the element on the cold fin. Because the gap thickness d is so small, the heat flow through the gap can be

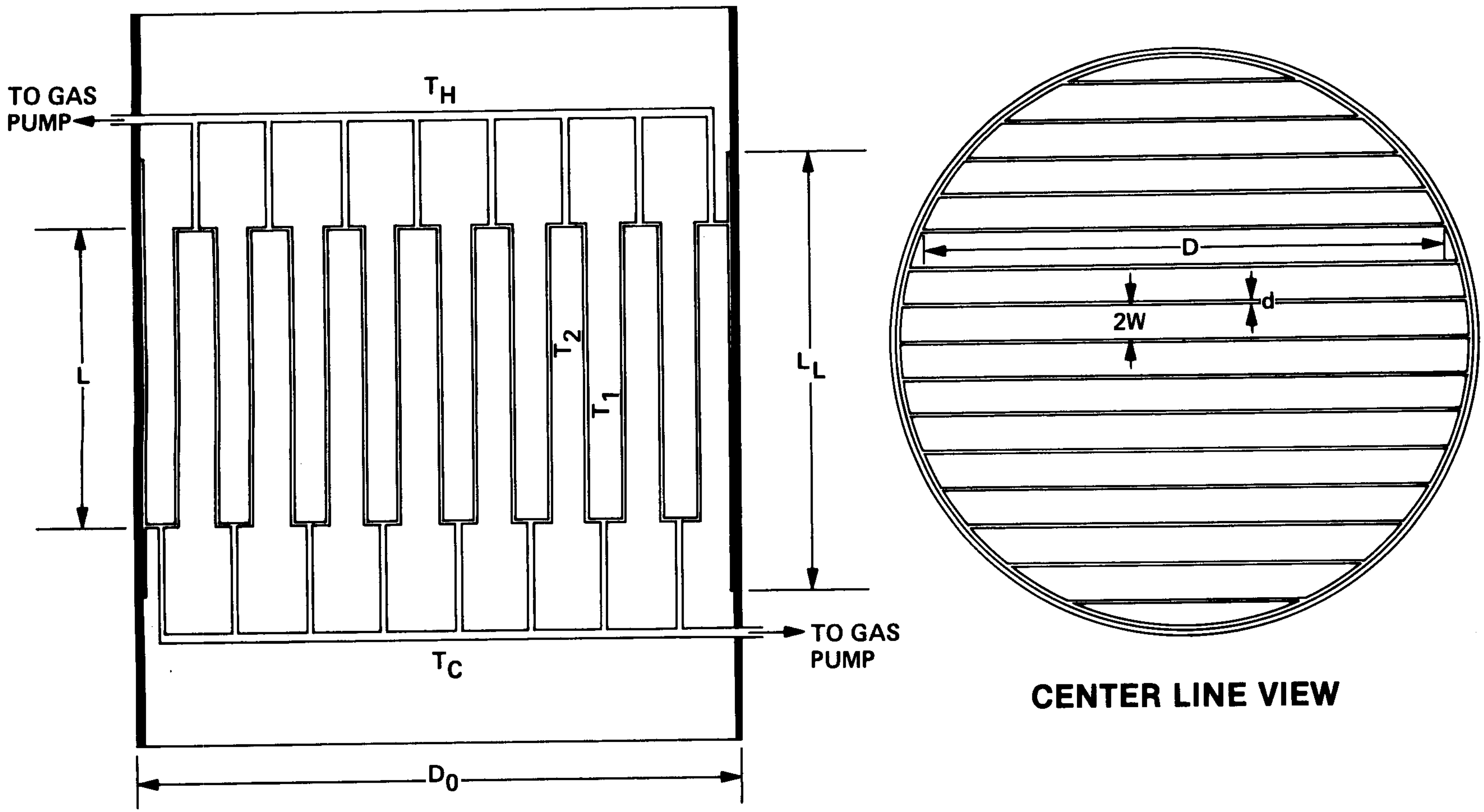

Figure 5.1. Straight Fins Heat Switch

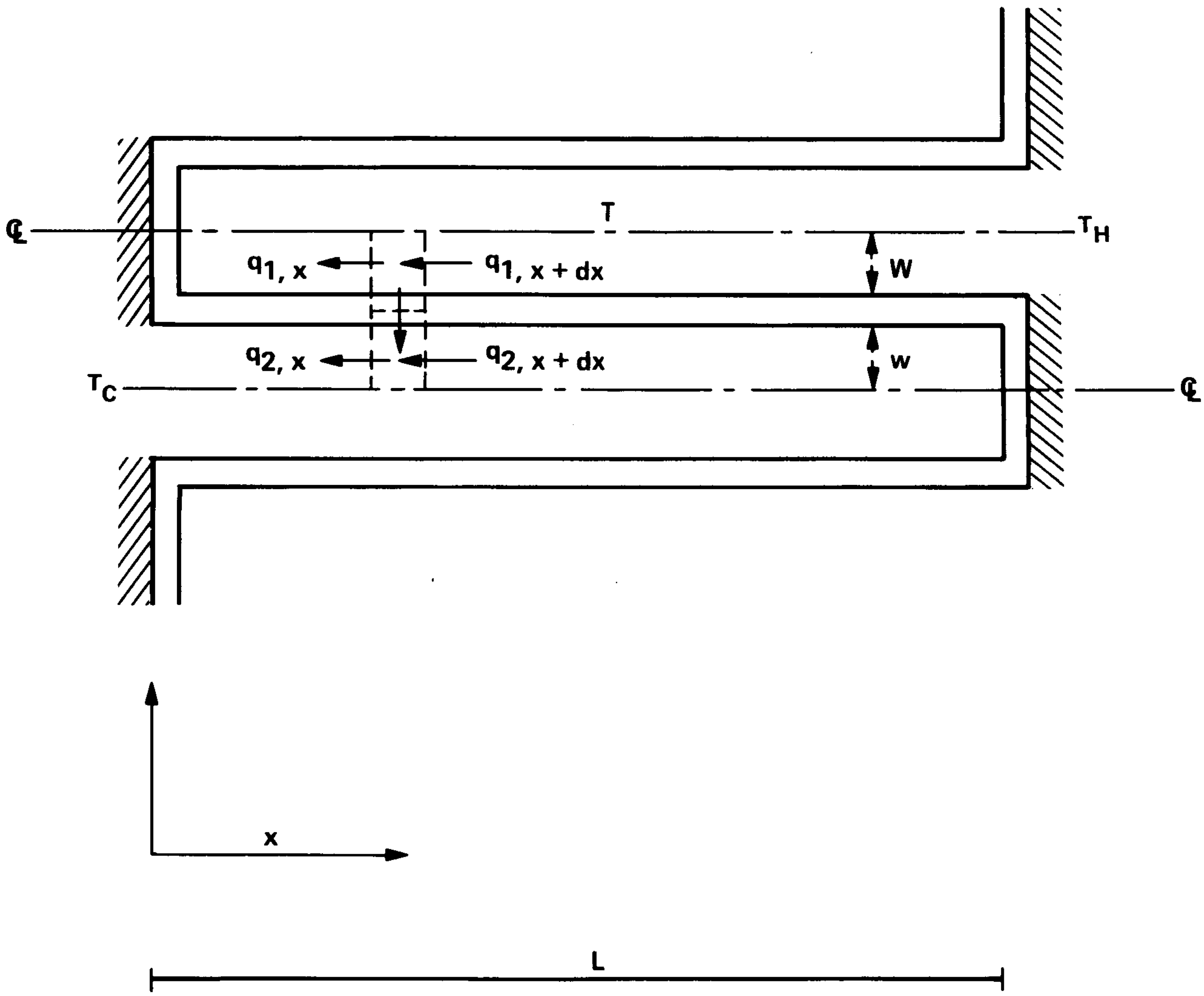

Figure 5.2. Physical Model of Heat Transfer Between a Pair of Hot and Cold Fins

assumed to be one-dimensional and to be determined by the local temperatures T_1 and T_2 of the hot and the cold fins, respectively. The amount of heat transferred Q_i from the hot element to the cold element is given by

$$Q_i = (Ddx)[\bar{\epsilon}\sigma_s(T_1^4 - T_2^4) + K(T_1 - T_2)] \qquad (5.2)$$

where

$\bar{\epsilon}$ = effective surface emittance between two parallel surfaces as defined by equation (2.2.12)
σ_s = Stefan –Boltzmann constant, W/cm^2K^4
K = gas conductance, k_g/d in the continuum regime and k_{fm}/d in the free molecular flow regime, W/cm^2K

If the temperatures T_1 and T_2 are close to each other, as in all the experimental tests, the radiation term can be approximated by

$$\sigma_s(T_1^4 - T_2^4) \simeq 4\,\sigma_s T_{av}^3\,(T_1 - T_2) \qquad (5.3)$$

where $4T_{av}^3 = (T_1 + T_2)\,(T_1^2 + T_2^2) = (T_H + T_C)(T_H^2 + T_C^2)$

By balancing the energy which enters and leaves the element, the differential equations for the cold and hot fins become

Hot side $$(q_{1,x+dx} - q_{1,x})wD = h_g(T_1 - T_2)Ddx \qquad (5.4)$$

Cold side $$(q_{2,x} - q_{2,x+dx})wD = h_g(T_1 - T_2)Ddx \qquad (5.5)$$

where

$$h_g = K + 4\sigma_s\bar{\epsilon}T_{av}^3 \quad W/cm^2K \qquad (5.6)$$

Replacing q_x by $-kdT/dx$ in equations (5.4) and (5.5), the differential equations for the temperature distributions along the fins are obtained

HOT SIDE $$\frac{d^2T_1}{dx^2} - \alpha_1^2(T_1 - T_2) = 0 \qquad (5.7)$$

COLD SIDE $$\frac{d^2T_2}{dx^2} + \alpha_2^2(T_1 - T_2) = 0 \qquad (5.8)$$

where

$$a_1^2 = \frac{h_g D}{A_1 k_1} \tag{5.9a}$$

$$a_2^2 = \frac{h_g D}{A_2 k_2} \tag{5.9b}$$

T_1, T_2 = temperatures of hot and cold fins respectively, K
k_1, k_2 = thermal conductivities of hot and cold fins respectively, W/cmK
A_1, A_2 = cross-sectional areas of hot and cold fins respectively, cm^2

$$a_1^2 = a_2^2 = a^2 = \frac{h_g D}{Ak} \qquad cm^{-2} \tag{5.10}$$

$$k = k_1 = k_2 \qquad W/cmK \tag{5.11}$$

$$A = A_1 = A_2 \qquad cm^2 \tag{5.12}$$

The boundary conditions for equations (5.7) and (5.8) are given by the known temperatures at the fin bases T_H and T_C and by the heat flow conditions at the fin tips where the heat is lost by conduction and radiation. However, since the end area wD is small compared to the total side area DL, as a first approximation it is necessary to take zero heat flow at the end. This leads to the four equations for the boundary conditions:

at x = 0

$$T_2 = T_C \tag{5.13}$$

$$\frac{dT_1}{dx} = 0 \tag{5.14}$$

at x = L

$$T_1 = T_H \tag{5.15}$$

$$\frac{dT_2}{dx} = 0 \tag{5.16}$$

WHERE

T_C = the base temperature of the cold fin

T_H = the base temperature of the hot fin

L = the length of the fin

The differential equations (5.7) and (5.8) together with the boundary conditions equations (5.13) to (5.16) can be solved analytically to yield a closed-form solution for T_1 and T_2 as function of x. For engineering applications, the heat flow between the fins would be of most interest. At steady state, this heat flow would be the same as the heat flow at the fin base

$$Q = -kA \left. \frac{dT_2}{dx} \right|_{x=0} \quad , W \tag{5.17}$$

and it is given by

$$Q = \frac{2kA\bar{a}\,(\Gamma_1 - \Gamma_2)}{\beta(\Gamma_1 - \Gamma_2) + 2(\Gamma_1 + \Gamma_2)}\,(T_H - T_C) \tag{5.18}$$

Knowing the heat flow, the equivalent conductance K_{eq} for the pair of the fins which is defined as

$$K_{eq} = \frac{Q}{T_H - T_C} \tag{5.19}$$

is given by putting equation (5.18) into equation (5.19)

$$K_{eq} = \frac{2\sqrt{(h_g D)\,(kA)2}\;(\Gamma_1 - \Gamma_2)}{\beta(\Gamma_1 - \Gamma_2) + 2(\Gamma_1 + \Gamma_2)} \tag{5.20}$$

where

$$\bar{a} = \sqrt{2}\,a \quad cm^{-1} \tag{5.21}$$

$$\beta = \bar{\alpha} L \tag{5.22}$$

$$\Gamma_1 = 1 + e^{\bar{\alpha} L} \tag{5.23}$$

$$\Gamma_2 = 1 + e^{-\bar{\alpha} L} \tag{5.24}$$

As a check to equation (5.20), when the fin conductivity k is very high so

$$kA >> h_g D \tag{5.25}$$

or

$$\beta \rightarrow O \tag{5.26}$$

and equation (5.20) is reduced to an asymptotic solution

$$K_{eq} \rightarrow h_g DL \tag{5.27}$$

Physically, when the fin conductivity is very high, the temperature will be uniform along the fin length and the only thermal resistance will be that across the gap.

At the other extreme, when the gap conductance is very high

$$h_g D >> kA \tag{5.28}$$

or

$$\beta \rightarrow \infty \tag{5.29}$$

equation (5.20) is reduced to

$$K_{eq} \rightarrow \frac{2kA}{L} \tag{5.30}$$

Physically the equivalent conductance is a linear combination of the fin conductances in series.

For a given gap conductance and fin material, the equivalent conductance can be expressed in a non-dimensional form as

$$\overline{K}_{eq} \equiv \frac{K_{eq}}{(h_g D)^{1/2}\ (kA)^{1/2}} \tag{5.31}$$

This non-dimensional conductance is a function of β

$$\frac{K_{eq}}{(h_g D)^{1/2}\,(kA)^{1/2}} = \frac{2\sqrt{2}\ (\Gamma_1 - \Gamma_2)}{\beta(\Gamma_1 - \Gamma_2) + \ 2\,(\Gamma_1 + \Gamma_2)} \tag{5.32}$$

where

$$\beta = \sqrt{2}\ \left(\frac{h_g D}{kA}\right)^{1/2} L \tag{5.33}$$

A plot of $\overline{K}_{eq}$ versus β is shown in Fig. 5.3. It is interesting to note that there is a maximum point for K_{eq} as β or the fin length L increases. Using the hardware dimensions, the values of β for the on mode are 0.5 and 0.2 for temperatures at 80 K and 20 K, respectively. This will be the starting point in the future for design optimization in terms of weight and efficiency.

For the fin configuration shown in Fig. 5.1, the total conductance K of fifteen pairs of fins are the summation of each individual pair plus the conductance through the support.

$$K = \sum_{i=1}^{n} (K_{eq})_i + K_L \qquad \text{(W/K)} \tag{5.34}$$

where

n = 15

$(K_{eq})_i$ = equation (5.20) for each pair i

$$K_L = \frac{k_L A_L}{L_L} \qquad \text{(W/K)} \tag{5.35}$$

k_L = thermal conductivity of support tube material, W/cmK

A_L = cross-sectional area of support tube, cm^2

L_L = length of support tube, cm

Putting the appropriate gap conductance during the on and the off

Putting the appropriate gap conductance during the on and the off modes of the switch, the on and off conductances, as well as the switch ratio of the conductance, can be computed.

$$K_{ON} = \sum_{i=1}^{n} (K_{eq})_{ON,i} + K_L \qquad (W/K) \qquad (5.36)$$

$$K_{OFF} = \sum_{i=1}^{n} (K_{eq})_{OFF,i} + K_L \qquad (W/K) \qquad (5.37)$$

$$S.R. = \frac{\sum_{i=1}^{n} (K_{eq})_{ON,i} + K_L}{\sum_{i=1}^{n} (K_{eq})_{OFF,i} + K_L} \qquad (5.38)$$

The switch ratio in a particular application when the heat flow during the on and the off modes of the switch are of more interest can be defined as

$$(S.R.)_Q = \frac{\left(\sum_{i=1}^{n} (K_{eq})_{ON,i} + K_L\right)\left(T_H - T_C\right)_{ON}}{\left(\sum_{i=1}^{n} (K_{eq})_{OFF,i} + K_L\right)\left(T_H - T_C\right)_{OFF}} \qquad (5.39)$$

where $(T_H - T_C)_{ON}$ and $(T_H - T_C)_{OFF}$ = temperature differences between the hot side and the cold side when the switch is on and off, respectively.

The use of these equations to predict the switch performance and the comparison between the prediction and the experimental data will be presented in the next Section.

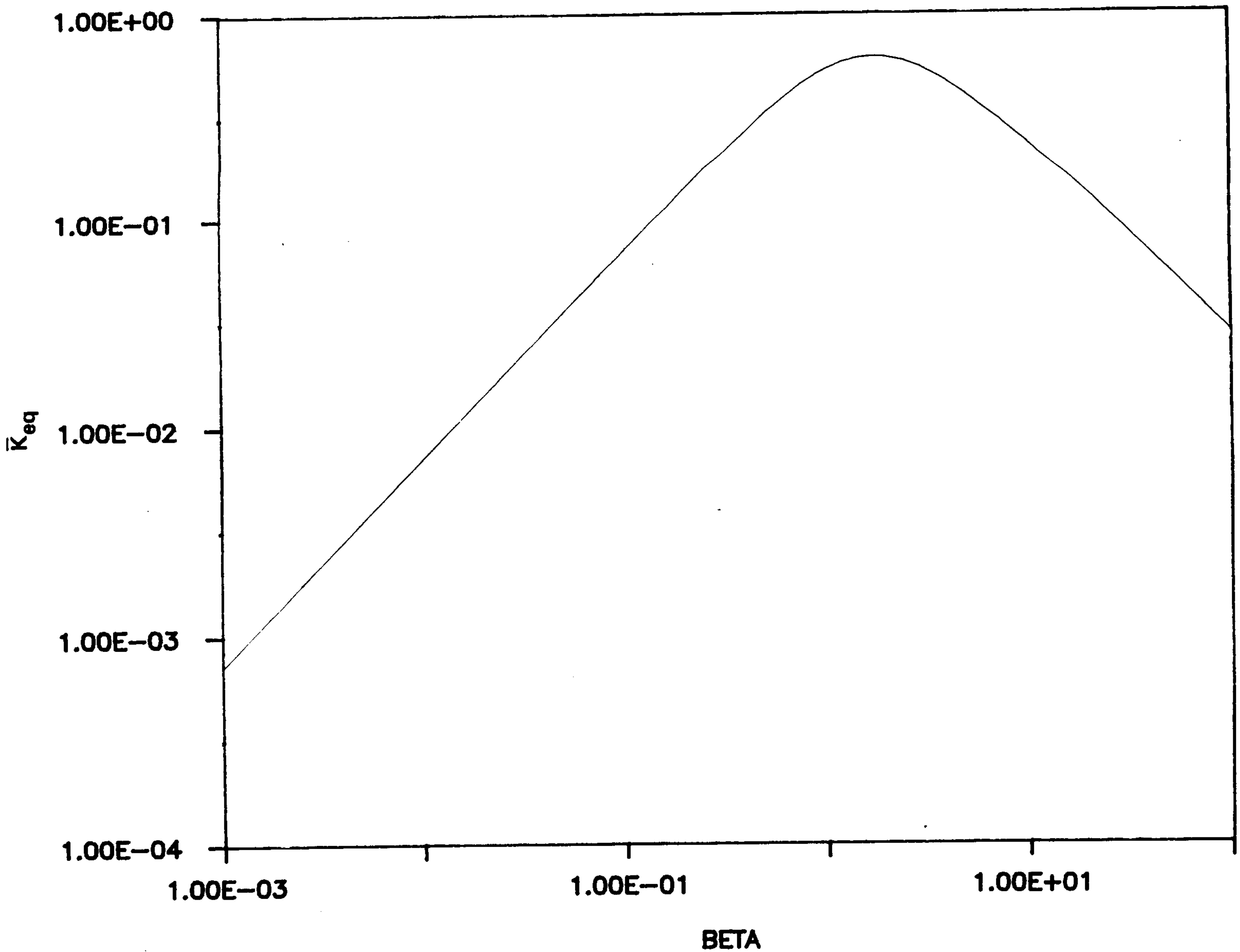

Figure 5.3. Non Dimensional Fin Conductance as Function of Beta

6.0 ANALYTICAL RESULTS AND TEST DATA COMPARISON

The numerical values of the closed-form solution developed in Section 5 are computed. They are then compared with the solution given by the thermal network. The comparison serves to verify the computer code HTSWCH. The test data are then compared with the numerical predictions by the closed-form solution and by the program HTSWCH.

6.1 Numerical Solution

Using the closed-form solution of the predictive model developed in the last section, the on conductance, the off conductance, and the switch ratio at three temperatures: 10 K, 20 K, and 80 K and at different gas pressures from 100 torr to 10^{-6} torr were calculated from equations (5.36), (5.37), and (5.38), respectively. The results are shown in Fig. 6.1 for the conductances and in Fig. 6.2 for the switch ratio. The calculation was based on the surface emissivity of 0.02. Other physical dimensions were based on the heat switch hardware that was built at JPL. At 80 K, when the pressure is less than 10^{-3} torr, the off conductance reaches the limit that is controlled by thermal radiation and support tube conductance, as the conductance due to thermal radiation K_R and through the support tube K_L are

Temperature	$K_R = 4\sigma T^3 A_f$, W/K	K_L, W/K
80 K	1.85×10^{-3}	3.78×10^{-3}
20 K	2.9×10^{-5}	1.15×10^{-3}
10 K	4×10^{-6}	4.67×10^{-4}

At 20 K and 10 K, the radiation limit is much lower. It is the support tube conductance that limits the off conductance which remains constant when pressures are less than 10^{-5} torr for the 20 K case, and less than 10^{-6} torr for 10 K. Since the on conductance is constant for a given temperature, these pressure limits also apply to the switch ratio. These findings agree in general with the results which were computed by the heat switch design program HTSWCH.

The effects of surface emissivity on these parameters were calculated for four values of emissivity. The calculated results are shown in Figs. 6.3 and 6.4 for the case of 80 K. At lower temperatures, the calculated results with different emissivities are not different from each other, hence, the case with the 0.02 emissivity shown in Figs. 6.1 and 6.2 can be used as the representative case. Even for the case of 80 K, the difference does not appear until the pressure falls below the limit when the lower surface emissivity tends to lower the off conductance.

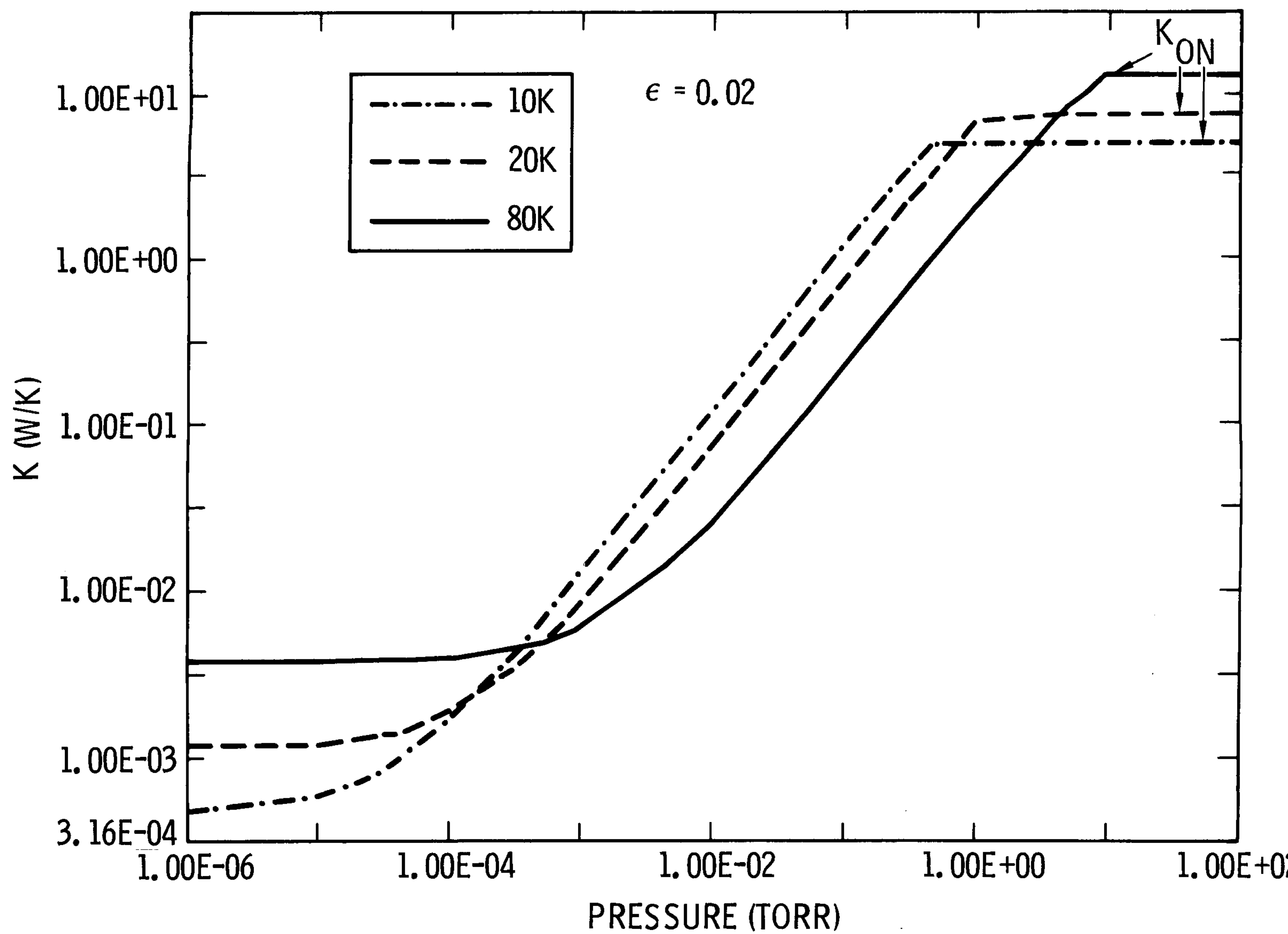

Figure 6.1. Calculated Heat Switch Conductance

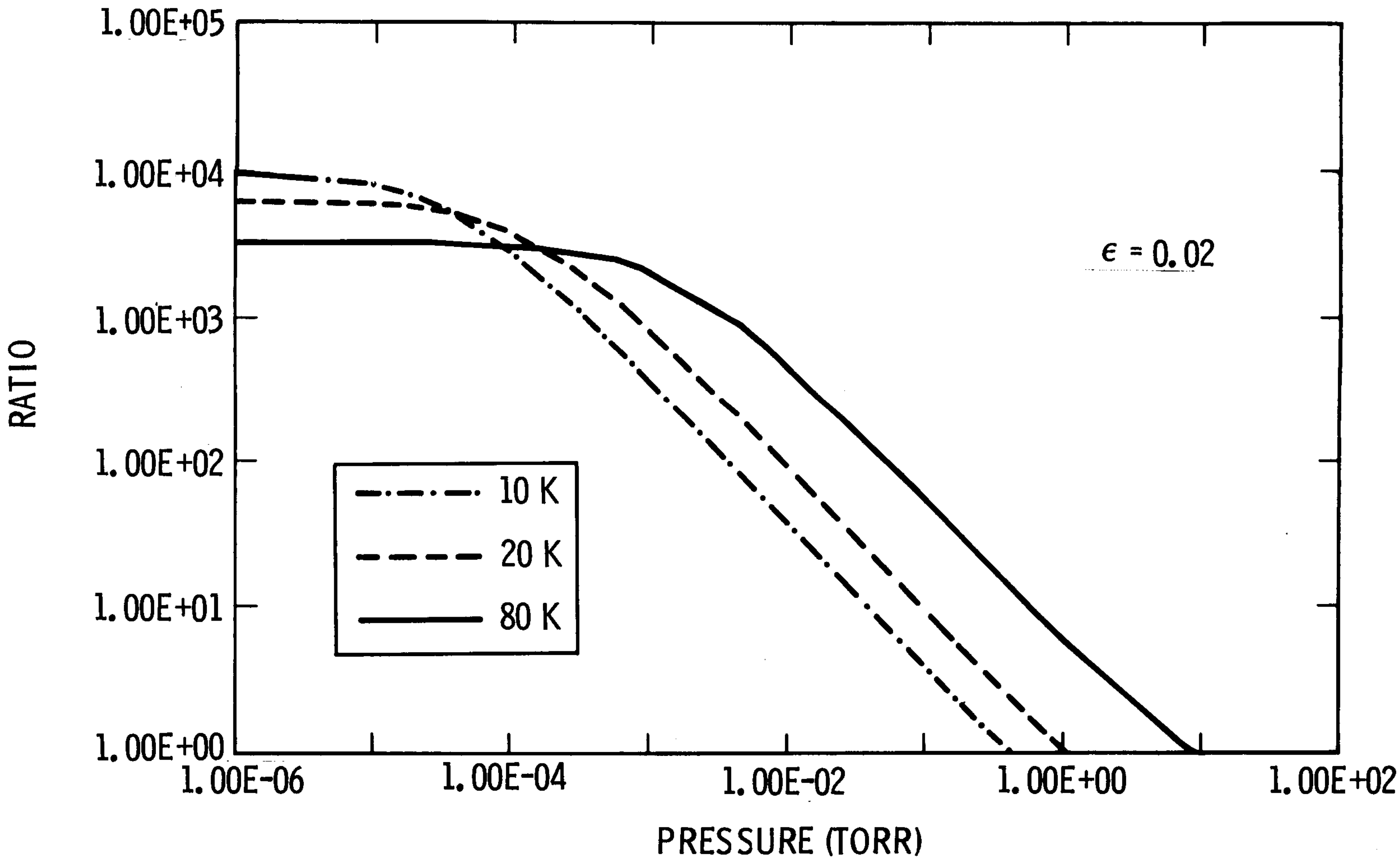

Figure 6.2. Calculated Heat Switch Ratios

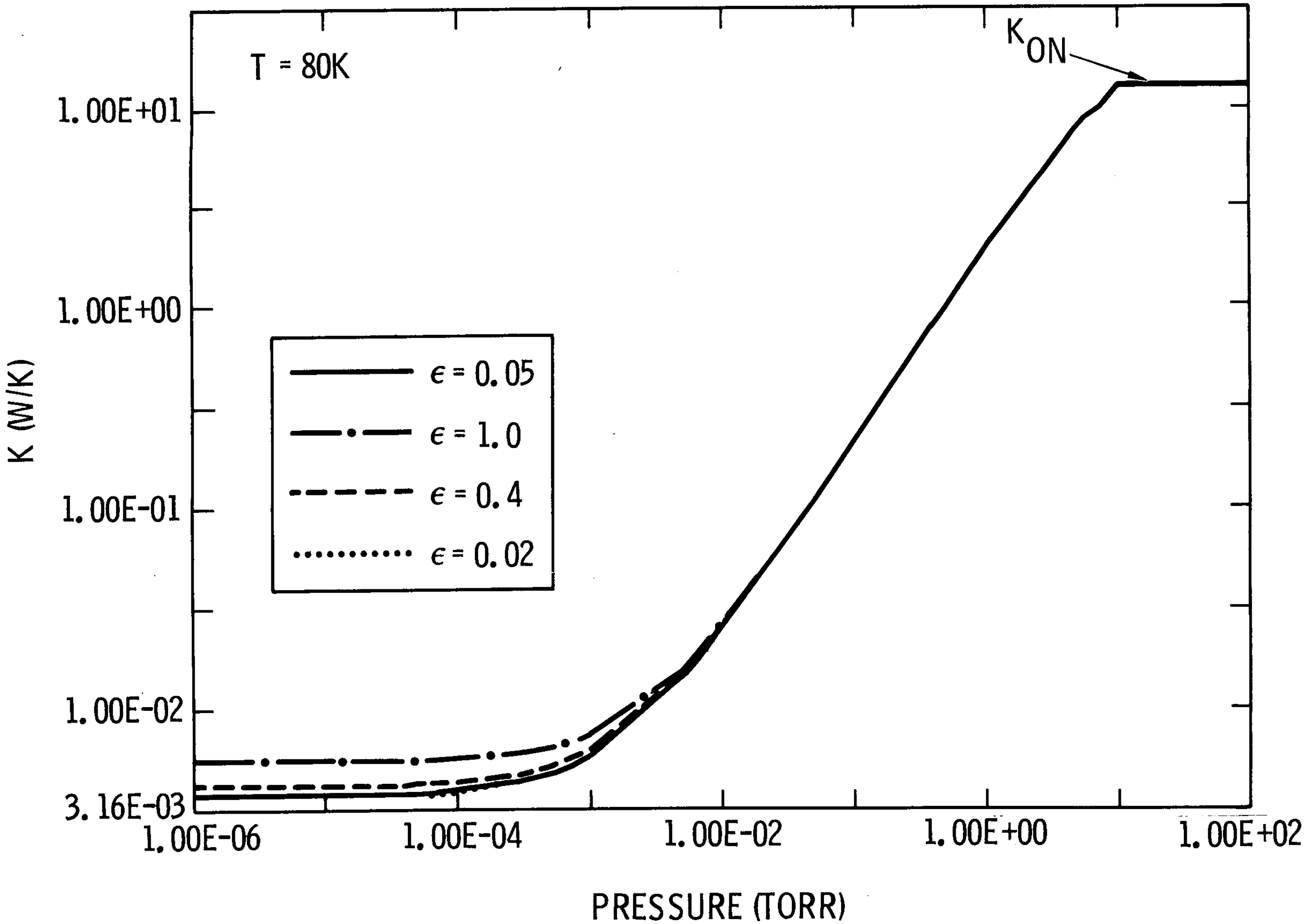

Figure 6.3. Calculated Heat Switch Conductance for Different Emissivities

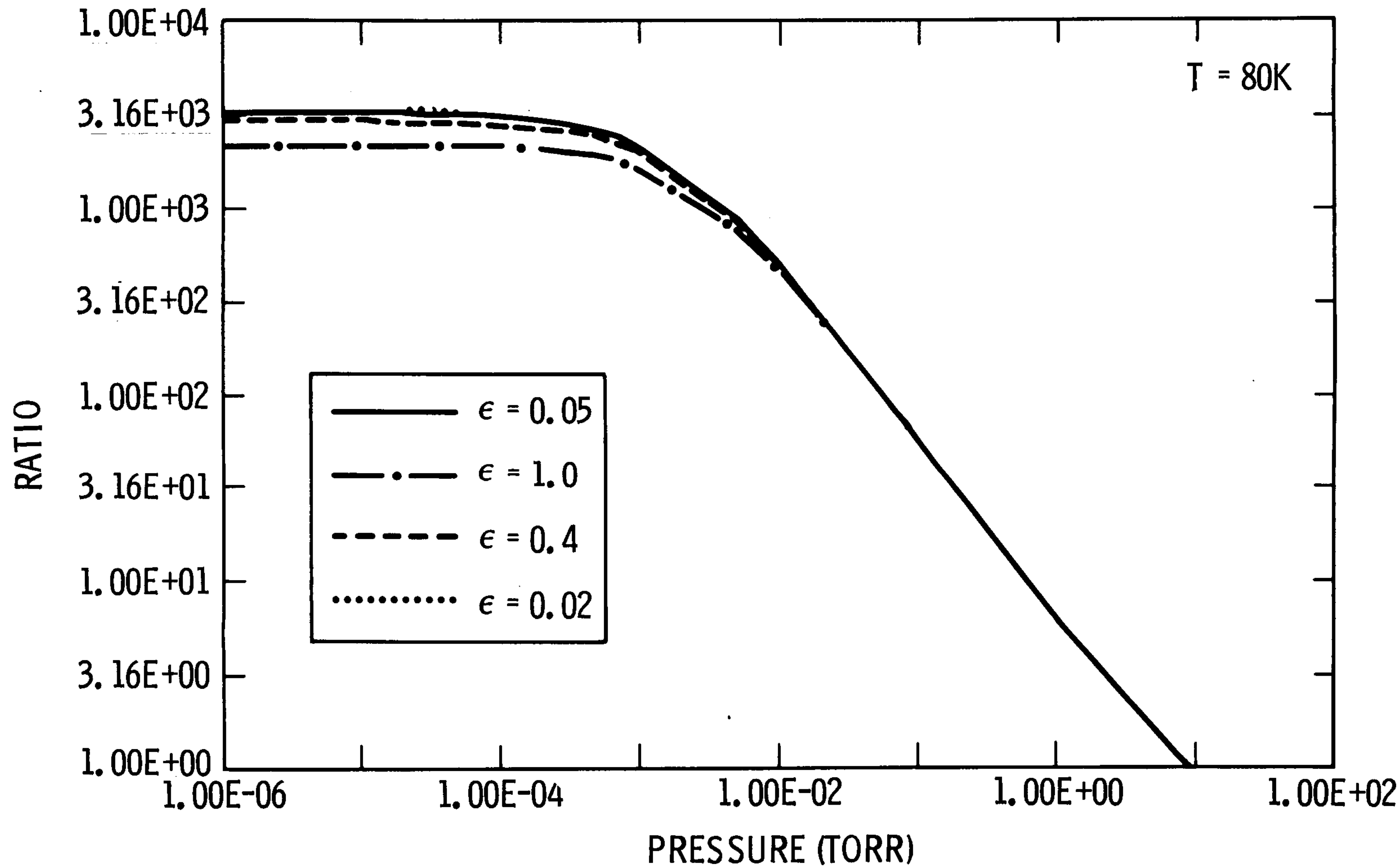

Figure 6.4. Calculated Heat Switch Ratios for Different Emissivities

6.2 Comparison of Models

Results from the two analytical methods, i.e., the thermal resistance method in Section 2.0 and the closed-form solution in Section 5.0 are presented in Table 6.1 using the same physical parameters as in the experiment. The results are very close to each other. This is due to the fact that when the system temperature is low, as in our test conditions, the interaction between the radiation and the conduction is weak. If the temperature on the hot side is high, radiation becomes important, and then there may be larger differences between the models.

6.3 Data Comparison

In comparison to the experimental tests, the predictive model in Section 5.0 for the multi-fin heat switch performance was used to calculate the on conductance, the off conductance, and the switch ratio at three temperatures: 10 K, 20 K, and 80 K. The techniques to obtain these parameters are summarized in Table 6.2 and the results are presented in Table 6.3, together with the experimental data tests. The only assumption in the calculation was that the gas pressure was to be 1 x 10^{-6} torr when the switch was off. The good comparison between the experimental and the analytical conductance data indicates that the pressure of the switch indeed reached 10^{-6} torr during the off mode, and this provided a good thermal isolation. The gas in the switch was in the continuum state during the on mode.

The test conditions of the helium gas experiments and the hydrogen gas experiments were input into the program HTSWCH which was based on the thermal network method. The input parameters were the temperature on the hot side T_H and the temperature on the cold side T_C. The gas was in the continuum state during the on mode and at 10^{-6} torr during the off mode. The surface emissivity was 0.4. The calculated heat flow Q_{anal} and the calculated conductance K_{anal} for 20 test points are presented in Table 6.4. The Q_{exp} is the Q which was obtained by the experiments in Section 4, while Q_{LEAK} is the adjusted heat determined by intersection of the Q versus ΔT curves at $\Delta T = 0$. If this Q_{leak} is adjusted from Q_{exp}, the resulting (Q_{exp} - Q_{leak}) values compare fairly well with the analytical results.

Table 6.1 Comparison Between the Two Analytical Methods

Surface Emissivity (ϵ)	Temperature (T)	Closed Form Solution (Sec. 5.0)			Thermal Network Method (Sec. 2.0)		
		K_{ON}	K_{OFF}	Ratio	K_{ON}	K_{OFF}	Ratio
0.02	10	4.9	4.8×10^{-4}	10,000	4.9	4.91×10^{-4}	9989
	20	7.5	1.2×10^{-3}	6400	7.5	1.16×10^{-3}	6488
	80	13	3.8×10^{-3}	3300	13.2	3.8×10^{-3}	3465
0.05	10	4.9	4.8×10^{-4}	10,000	4.9	4.91×10^{-4}	9989
	20	7.5	1.2×10^{-3}	6400	7.5	1.16×10^{-4}	6488
	80	13	3.8×10^{-3}	3300	13.2	3.83×10^{-3}	3438
0.4	10	4.9	4.8×10^{-4}	10,000	4.9	4.91×10^{-4}	9989
	20	7.5	1.2×10^{-4}	6400	7.5	1.16×10^{-3}	6488
	80	13	4.3×10^{-3}	3000	13.2	4.26×10^{-3}	3090
1.0	10	4.9	4.8×10^{-4}	10,000	4.9	4.95×10^{-3}	9912
	20	7.5	1.2×10^{-3}	6300	7.5	1.19×10^{-3}	6319
	80	13	5.6×10^{-4}	2200	13.2	5.7×10^{-4}	2309

Table 6.2 Comparison of Methodology Between Experimental Data Deduction and Numerical Comparison

Parameters	Data Deduction Methodology	Numerical Computation
On Conductance	K_{ON} = gradients of Q vs. ΔT	Continuum Gas Conductivity and Thermal Radiation and Support Tube Conduction
Off Conductance	$K_{OFF} = Q / \Delta T$	Gas Conductivity at P=10E-6 torr and Thermal Radiation and Support Tube Conductance
Switch Ratio	$S.R. = \dfrac{K_{ON,\ Experimental}}{K_{OFF,\ Experimental}}$	$\dfrac{K_{ON,\ Analytical}}{K_{OFF,\ Analytical}}$

Table 6.3. Experimental and Analytical Values of On Conductance, Off Conductance and Switch Ratio of the Straight Fins Heat Switch

Temperature	On Conductance(W/K)		Off Conductance(W/K)		Switch Ratio	
	Experimental	Analytical	Experimental	Analytical	Experimental	Analytical
10 K	4.9	4.9	4.50E-4	4.80E-4	10900	10208
20K	8.0	7.5	1.07E-3	1.20E-3	7500	6300
80K	11	13	4.90E-3	6.40E-3	2245	2301

Table 6.4 Comparison of Test Data with the Calculation Performed by the Program HTSWCH

Gas Used	Condition	Exp #	TH (K)	TC (K)	T (K)	Q_{exp} (w)	Q_{leak} (w)	Q_{exp}-Q_{leak} (w)	Q_{anal} (w)	K_{exp} (w/k)	K_{anal} (w/k)
He	10K	89	8.69	4.19	4.5	2.06×10^{-3}	6×10^{-4}	1.46×10^{-3}	1.32×10^{-3}	3.24×10^{-4}	2.93×10^{-4}
Gas	Range	87A	10.06	4.19	5.87	2.56×10^{-3}	6×10^{-4}	1.96×10^{-3}	1.93×10^{-3}	3.33×10^{-4}	3.29×10^{-4}
	Off mode	88	11.79	4.19	7.6	3.42×10^{-3}	6×10^{-4}	2.82×10^{-3}	2.84×10^{-3}	3.71×10^{-4}	3.73×10^{-4}
	10K	90	9.72	9.17	0.55	1.602	-1.02	2.66	2.53	4.84	4.6
	Range		10.62	10.01	0.61	1.90	-1.02	2.96	3.01	4.85	4.93
	On mode		11.16	10.52	0.64	2.12	-1.02	3.18	3.28	4.97	5.13
	20K	97	20.93	15.33	5.6	6.07×10^{-3}	-7.6×10^{-5}	6.14×10^{-3}	5.55×10^{-3}	1.09×10^{-3}	9.91×10^{-4}
	Range	98	22.28	15.07	7.21	7.36×10^{-3}	-7.6×10^{-5}	7.44×10^{-3}	7.44×10^{-3}	1.03×10^{-3}	1.03×10^{-3}
	Off mode	99	23.87	15.02	8.85	9.01×10^{-3}	-7.6×10^{-5}	9.08×10^{-3}	9.65×10^{-3}	1.02×10^{-3}	1.09×10^{-3}
	20K	101	20.55	18.58	1.97	8.63	-5.02	13.65	14.35	6.93	7.29
	Range		22.22	20.05	2.17	10.61	-5.02	15.63	16.6	7.21	7.65
	On mode		18.68	16.96	1.72	6.9	-5.02	11.92	11.81	6.93	6.87
	80K	84	81.88	76.97	4.91	0.0199	-2.9×10^{-4}	0.0202	0.0205	4.11×10^{-3}	4.17×10^{-3}
	Off mode	83	87.85	76.99	10.86	0.0476	-2.9×10^{-4}	0.0479	0.0474	4.41×10^{-3}	4.36×10^{-3}
	80K	90B	78.38	78.12	0.26	1.67	-1.4	3.07	3.398	11.81	13.07
	On mode		78.61	78.32	0.29	1.99	-1.4	3.40	3.792	11.72	13.07
H2	80K	30	91.44	77.57	13.88	0.072	0.012	0.0601	0.0627	4.33×10^{-3}	4.52×10^{-3}
Gas	Off mode	31	95.24	77.62	17.62	0.096	0.012	0.084	0.0821	4.77×10^{-3}	4.66×10^{-3}
	80K	16	80.21	79.66	0.55	3.94	-1.6	5.54	6.42	10.1	11.68
	On mode	17	81.57	80.80	0.77	6.16	-1.6	7.76	9.05	10.1	11.75

7.0 HEAT SWITCH INTERFACE

When the heat switch is used with the redundant three-stage VM or Stirling coolers (Fig. 2.25) there are several interface problems that need to be addressed:

(1) the equilibrium temperature profile of the cold fingers of the non-operational refrigerator,

(2) the steady state heat leak of the system,

(3) the transient cooldown of the optical plane and the cold finger, and

(4) the vibration isolation function of the heat switch.

At present, only the first two items will be addressed. The interface of the heat switches with the refrigeration systems and the cold plates can be analyzed by a thermal network (Fig. 7.1). With nine nodal points representing the three stages of the operational refrigeration having masses of M_{03}, M_{02}, and M_{01}, at temperatures T_{03}, T_{02}, and T_{01}, the stages of the non-operational refrigerator have masses of M_{N3}, M_{N2}, and M_{N1} at temperatures T_{N3}, T_{N2}, and T_{N1}. The masses of the cold plates are M_{C3}, M_{C2}, and M_{C1} at temperatures T_{C3}, T_{C2}, and T_{C1}.

If T_e is the environmental temperature of the spacecraft, R_{03}, R_{02}, R_{01}, and R_{N3}, R_{N2}, R_{N1} represent the thermal resistances between the stages at the refrigerators. Then, R_{P3}, R_{P2}, and R_{P1} are the reciprocals of the on conductance of the heat switch; R_{F3}, R_{F2}, and R_{F1} are the reciprocals of the off conductance of the heat switch. By making a heat flow balance at each nodal point, the following nine equations are obtained:

$$\frac{T_e - T_{N1}}{R_{N1}} = \frac{T_{N1} - T_{C1}}{R_{F1}} + \frac{T_{N1} - T_{N2}}{R_{N2}} \tag{7.1}$$

$$\frac{T_{N1} - T_{N2}}{R_{N2}} = \frac{T_{N2} - T_{C2}}{R_{F2}} + \frac{T_{N2} - T_{N3}}{R_{N3}} \tag{7.2}$$

$$\frac{T_{N2} - T_{N3}}{R_{N3}} = \frac{T_{N3} - T_{C3}}{R_{F3}} \tag{7.3}$$

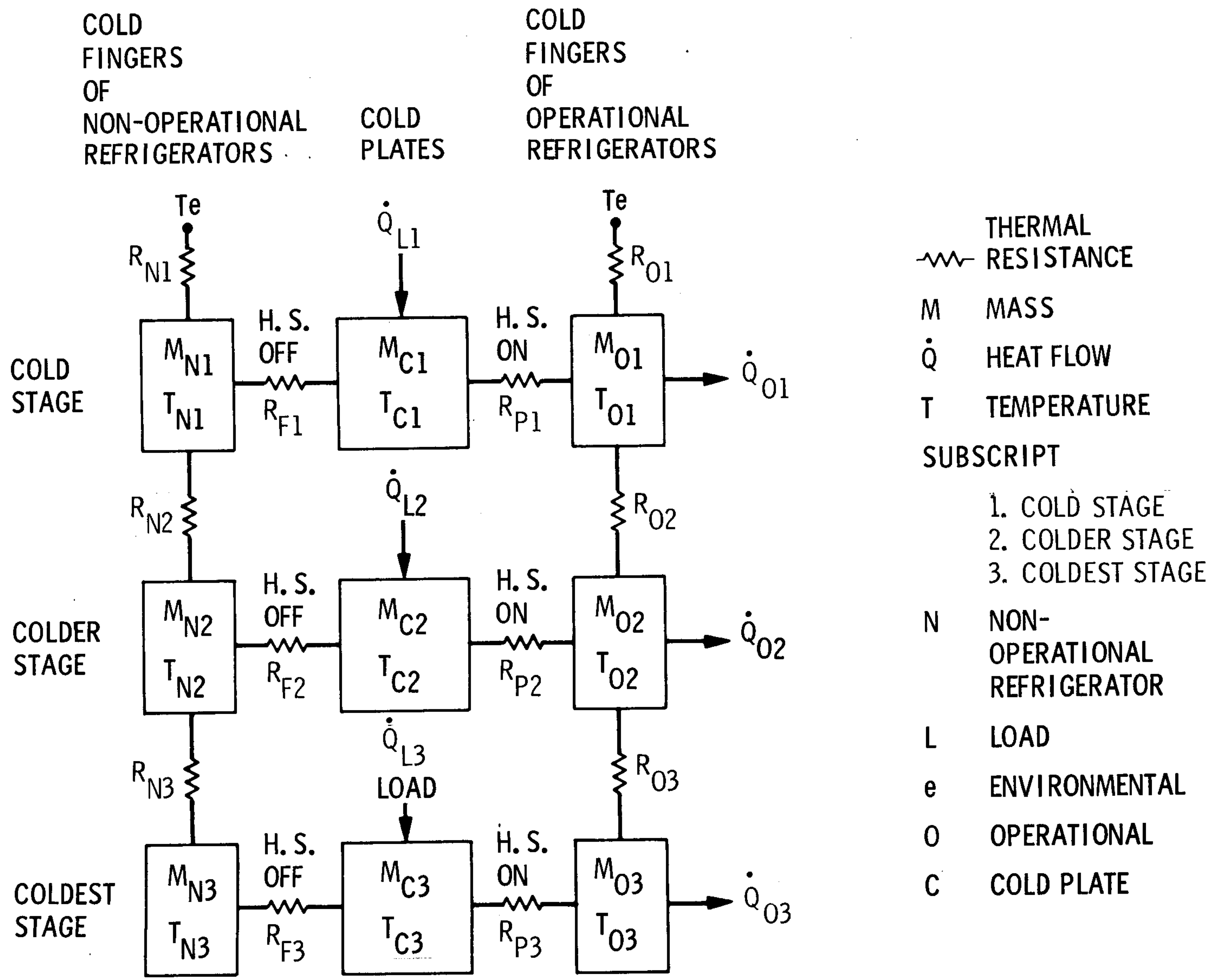

Figure 7.1. Thermal Circuit of Heat Switch Interface

$$\frac{T_{N1} - T_{C1}}{R_{F1}} + Q_{L1} = \frac{T_{C1} - T_{01}}{R_{P1}} \tag{7.4}$$

$$\frac{T_{N2} - T_{C2}}{R_{F2}} + Q_{L2} = \frac{T_{C2} - T_{02}}{R_{P2}} \tag{7.5}$$

$$\frac{T_{N3} - T_{C3}}{R_{F3}} + Q_{L3} = \frac{T_{C3} - T_{03}}{R_{P3}} \tag{7.6}$$

$$\frac{T_e - T_{01}}{R_{01}} + \frac{T_{C1} - T_{01}}{R_{P1}} = Q_{01} + \frac{T_{01} - T_{02}}{R_{02}} \tag{7.7}$$

$$\frac{T_{01} - T_{02}}{R_{02}} + \frac{T_{C2} - T_{02}}{R_{P2}} = Q_{02} + \frac{T_{02} - T_{03}}{R_{03}} \tag{7.8}$$

$$\frac{T_{02} - T_{03}}{R_{03}} + \frac{T_{C3} - T_{C2}}{R_{P3}} = Q_{03} \tag{7.9}$$

The analysis was applied to two redundant cryocoolers with approximate heat loads of 300 mW, 2 W, and 8.3 W, at the third, the second, and the first stages, respectively. The heat switch was sized so it would provide the heat transfer between 85 K and 80 K at the first stage, between 22 K and 20 K at the second stage, and between 9 K and 8 K at the third stage. These yield the on resistances at the three stages

$$R_{p1} = 0.6\ \text{K/W} \tag{7.10}$$

$$R_{p2} = 1.05\ \text{K/W} \tag{7.11}$$

$$R_{p3} = 3.33\ \text{K/W} \tag{7.12}$$

Assuming that when the switch is off, the switch ratios of the present heat switch still apply, so

$$R_{N1} = (S.R.)_{80} R_{P1} \tag{7.13}$$

$$R_{N2} = (S.R.)_{20} R_{P2} \tag{7.14}$$

$$R_{N3} = (S.R.)_{10} R_{P3} \tag{7.15}$$

In some cases, it may be more desirable to keep the switch on at the first or the second stage of the non-operational refrigeration. In those cases:

$$R_{Ni} = R_{pi} \tag{7.16}$$

The thermal resistance between the stages of the cryocoolers was based on approximating the resistance of a titanium bar with a 1 inch x 1 inch square base. The distance between the third and the second stages and between the second and the first stages is 6 inches, and the distance between the first stage and the room temperature is 12 inches, (Fig. 7.2). Since the conductivity of titanium changes with temperature, the resistances R_{01}, R_{02}, R_{03} and R_{N1}, R_{N2}, R_{N3} will depend on the local temperature of each stage. Because of this, an iterative method was used to solve equations (7.1) to (7.9) for the temperatures at the non-operational refrigerators T_{N1}, T_{N2}, and T_{N3} and the heat loads on the cold plates Q_{L1}, Q_{L2}, and Q_{L3} and on the operational refrigerator Q_{01}, Q_{02}, and Q_{03} as well as the heat leaks to the environment. These parameters were computed by the computer code HSINTFC2. A sample run is shown in Appendix D. Four cases were considered:

(1) all the heat switches are on,

(2) only the heat switch at the third stage of the non-operational refrigerator is off,

(3) both heat switches at the third and second stages are off, and

(4) all heat switches of the non-operational refrigerator are off.

The ratio between R_{Ni} and R_{pi} for these four cases is shown in Table 7.1.

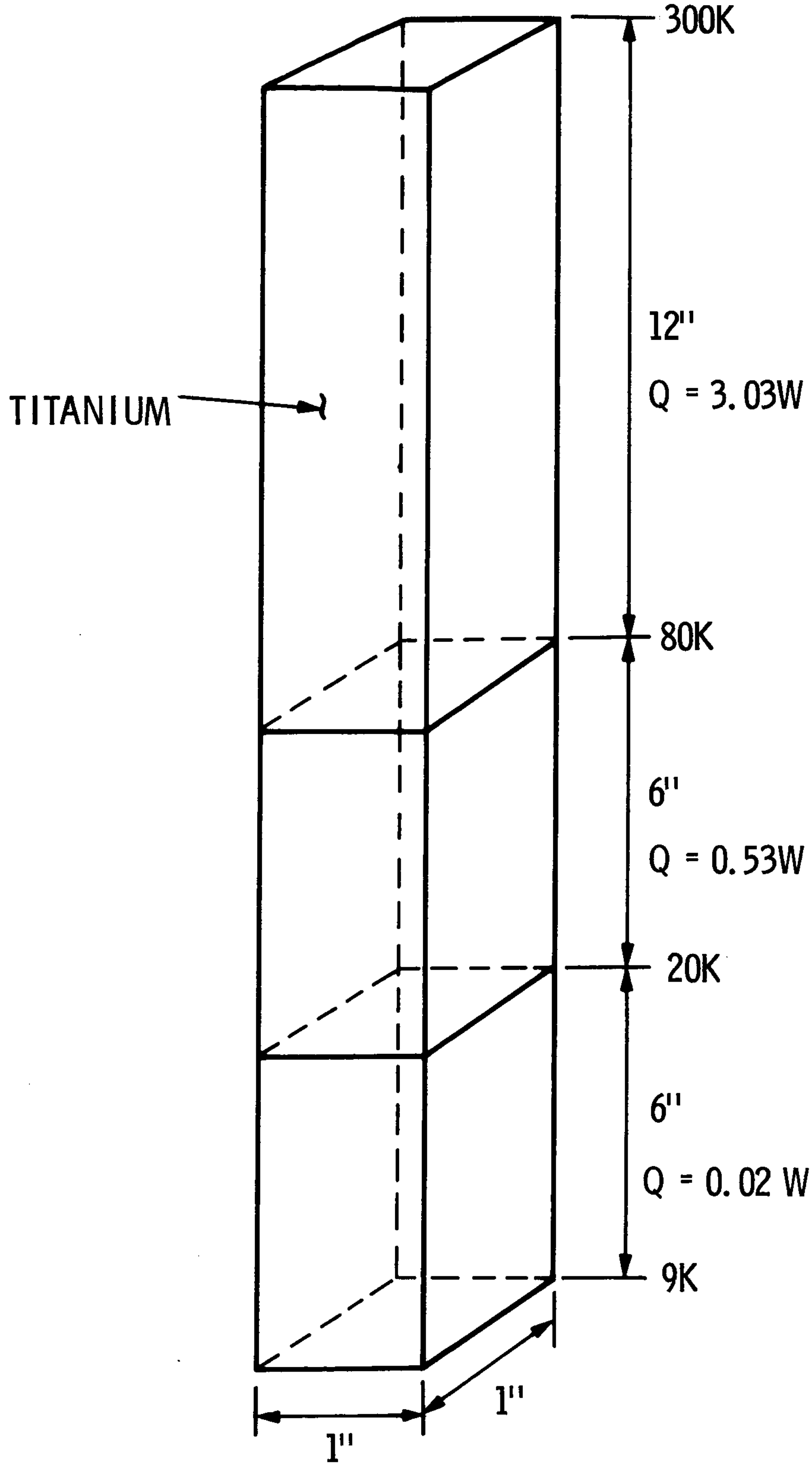

Figure 7.2. Equivalent Thermal Resistance of 3-Stage VM-Cooler

Table 7.1 Switch Ratios for the Four Cases

Case #	A	B	C	D
$Ratio_3$	1	10900	10900	10900
$Ratio_2$	1	1	7500	7500
$Ratio_1$	1	1	1	2245

The results are shown in Figs. 7.3 to 7.6. In case A, when all the switches are on, the temperature at the third stage of the non-operational refrigerators is close to the cold plate temperature, and the heat load at the third stage is 0.27 W. In case B, when the switch at the third stage is off, the heat load at the third stage increases to 0.30 W while the temperature at the third stage will be at 22.48 K. The heat leak remains unchanged from case A. In case C, when the switch at the second stage is also off, the refrigerator temperature at the third stage rises to 85 K. In the last case D, when all the switches that are linked to the non-operational refrigerator are off, the temperatures of that refrigerator jump to 280 K. The heat load at the third stage is actually reduced to 0.29 W. However, the total heat leak from the system is much reduced. Hence, it may be advantageous to keep the heat switch at the first stage of low switch ratio as in case C, when the heat load at the coldest stage reaches the maximum. It should be cautioned that these calculations were based on hypothetical numbers, and they should be used for illustration only.

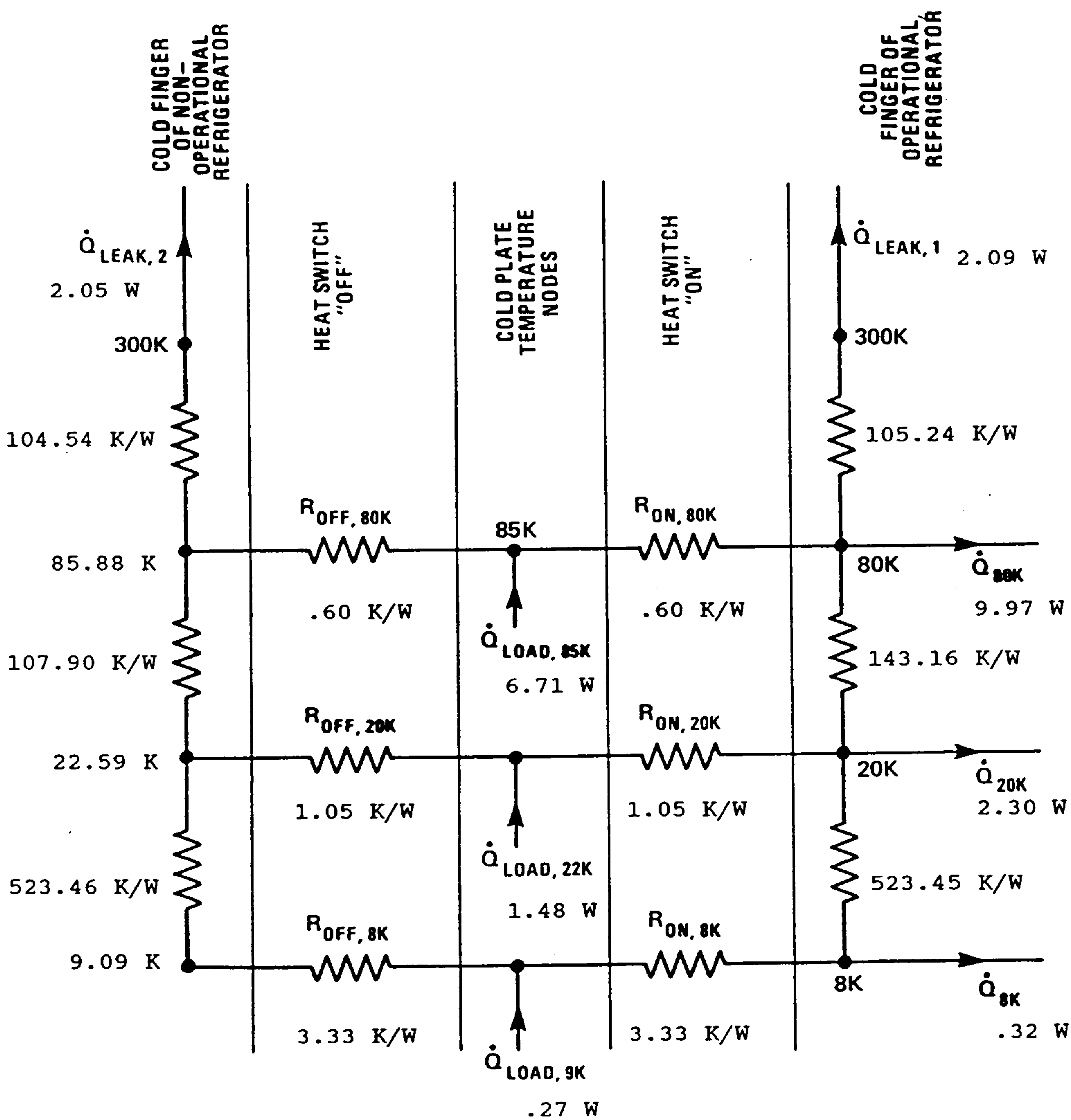

Figure 7.3. Thermal Network of Heat Switch Interface with Three-Stage Refrigeration Systems (Case A)

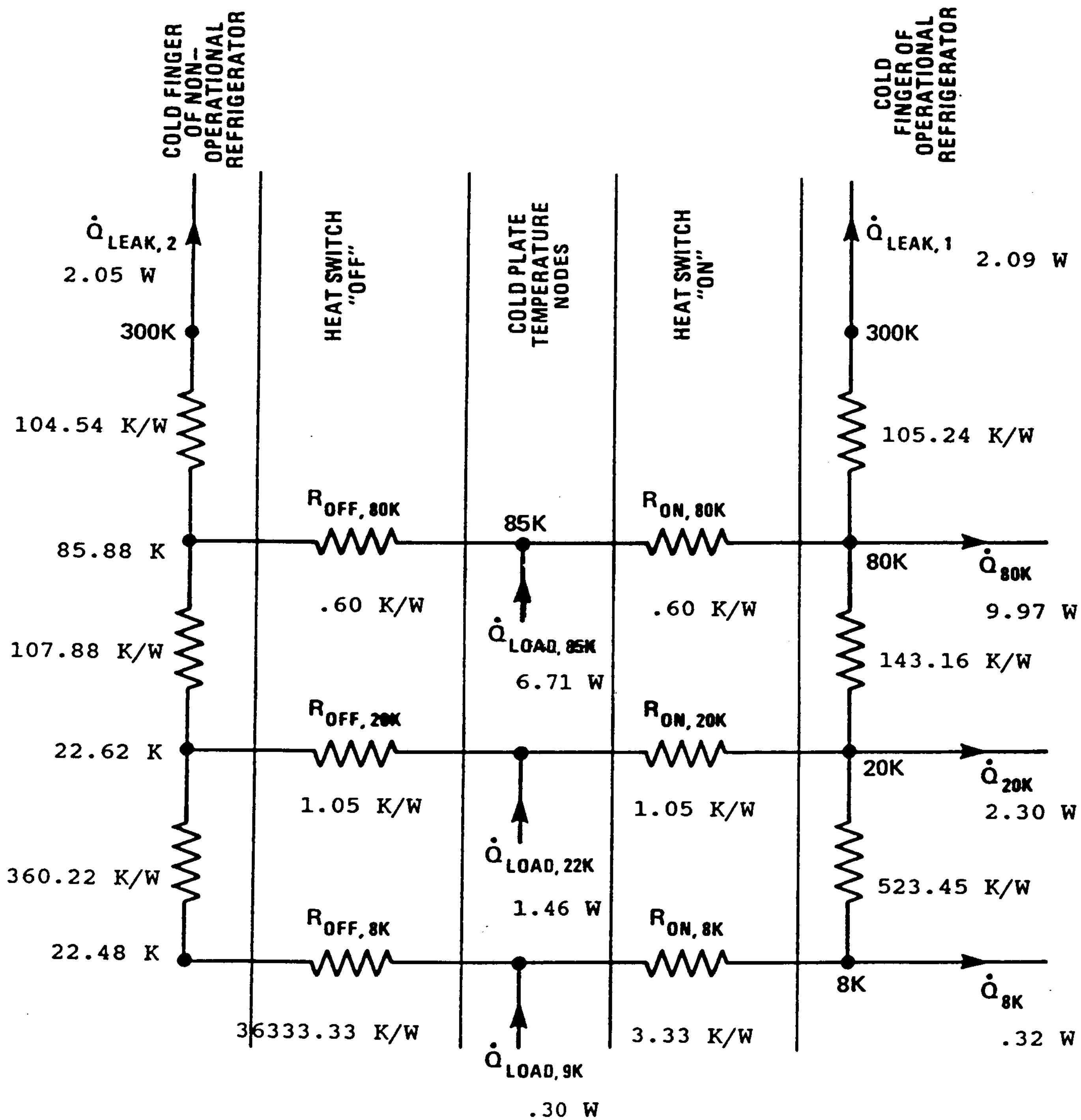

Figure 7.4 Thermal Network of Heat Switch Interface with Three-Stage Refrigeration Systems (Case B)

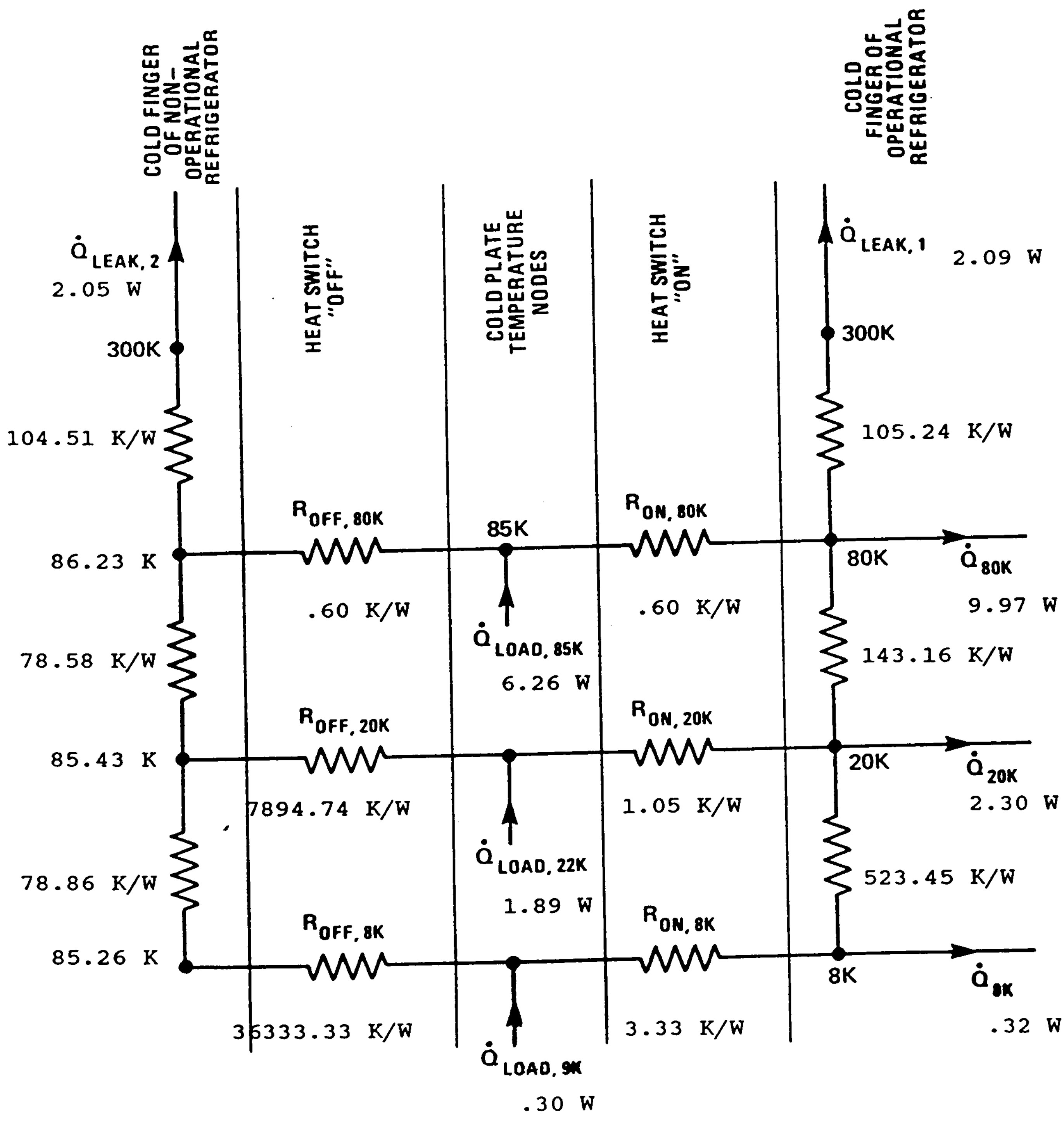

Figure 7.5 Thermal Network of Heat Switch Interface with Three-Stage Refrigeration Systems (Case C)

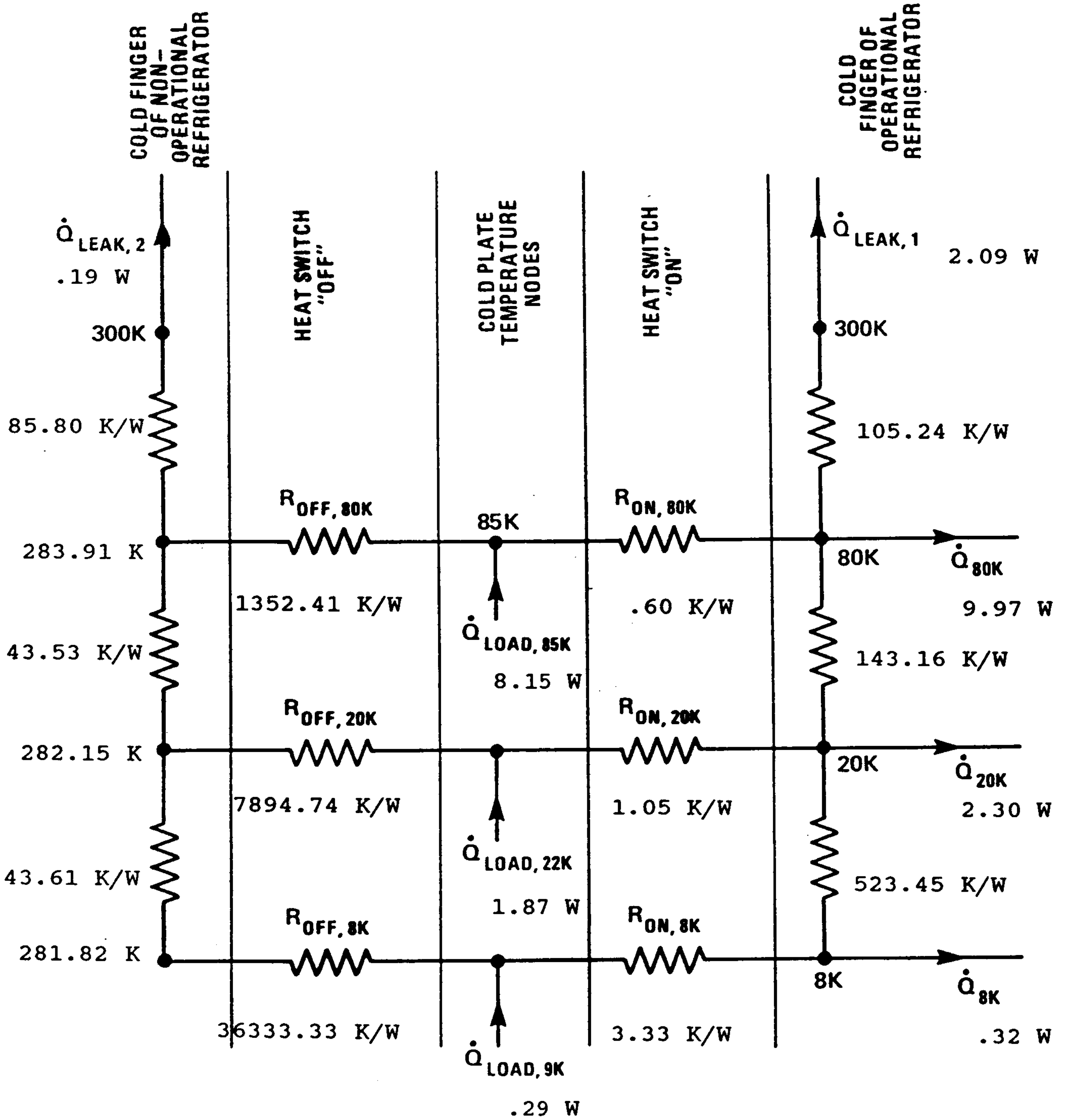

Figure 7.6 Thermal Network of Heat Switch Interface with Three-Stage Refrigeration Systems (Case D)

8.0 CONCLUSIONS

To reduce the parasitic heat loss, a self-actuated heat switch system for redundant cryocoolers was invented. The basic component of the system is the gas adsorption heat switch which is comprised of many extended surfaces. This new concept was transformed into the hardware by analyses, design, and fabrication. The switch was tested at temperature ranges of potential application. This initial phase of testing demonstrates the high performance of the design. Both the tests and the analyses have provided fundamental understanding of the heat switch performance and defined the limiting factors. The switch ratio of over 10,000 obtained by this first-round design demonstrates the technical feasibility. Repeated use of the adsorption pump for different gases at different temperatures shows no sign of degradation. Repeated tests also show consistent data. Hence, the present design will be extremely reliable for repeated operations. The interface analysis is the first step towards how the heat switches can be implemented for the redundant cryocoolers. Other interface problems, such as the heat leaks due to cross-strapping and transient response time, will be addressed in the future. However, the fundamental knowledge obtained from the present tests and analyses should be useful in new system designs where the useful life of future space missions can be greatly prolonged.

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APPENDIX A
HTSWCH:A HEAT SWITCH DESIGN PROGRAM

The program HTSWCH can be run from any IBM PC, XT, or AT or their equivalent. At the prompt, the following is entered to execute the program:

B:\HTSWCH <RETURN>

The menu shown in Table A.2 appears on the screen. The user has the option to either alter any of the 15 choices or continue with the program. The wall material could be glass, stainless steel, or G10; the fin material could be copper TP or copper; the gas could be hydrogen or helium; and the surface emissivity could be any value. By inputting 0 to the question, "Any more changes? (1=yes, 0=no)," the program will move from the input mode to the computation mode.

The program first prints out the 15 parameters and then the width D, the area A, and the cross-sectional area A_c of each of the eight fins. The total area refers to the heat transfer area through the 15 gaps shown in Fig. A.1. The program then computes the heat transfer parameters when the gas in the gap is on the continuum state, i.e., when the switch is on. After printing out the thermal conductivities of

(1) the gas Kg,
(2) the fin material on the hot side KmH,
(3) the fin material on the cold side KmC, and
(4) the material of the support tube KL,

the program computes the thermal resistances as shown in Fig. A.2. These resistances are the reciprocals of the conductances in Section 2.2, where

(1) RFH = thermal resistance of half of the fin, and the gas gap on the hot side,
(2) RFC = thermal resistance of half of the fin and the gas gap on the cold side,
(3) RF = RFH+RFC,
(4) RR = thermal resistance due to thermal radiation across the gap,
(5) RG = thermal resistance of the gas in the gap neglecting the fin resistance, and
(6) RL = thermal resistance of the support tube.

Then, the heat flows from the hot side to the cold side due to

(1) the combined fin and gas conductance = QG,
(2) the thermal radiation across the gap = QR,
(3) the support tube conductance = QL, and

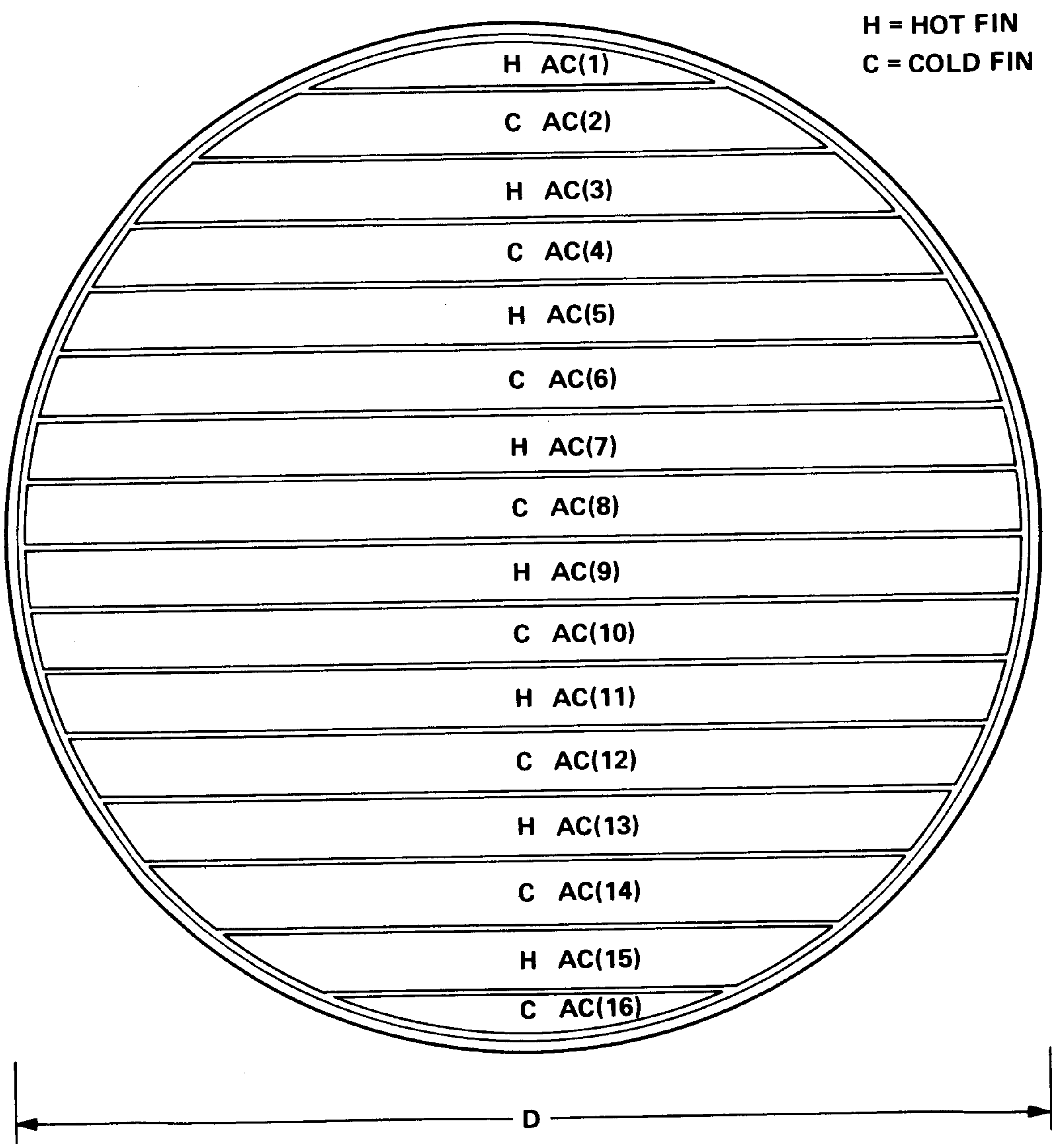

Figure A.1. Fin Model

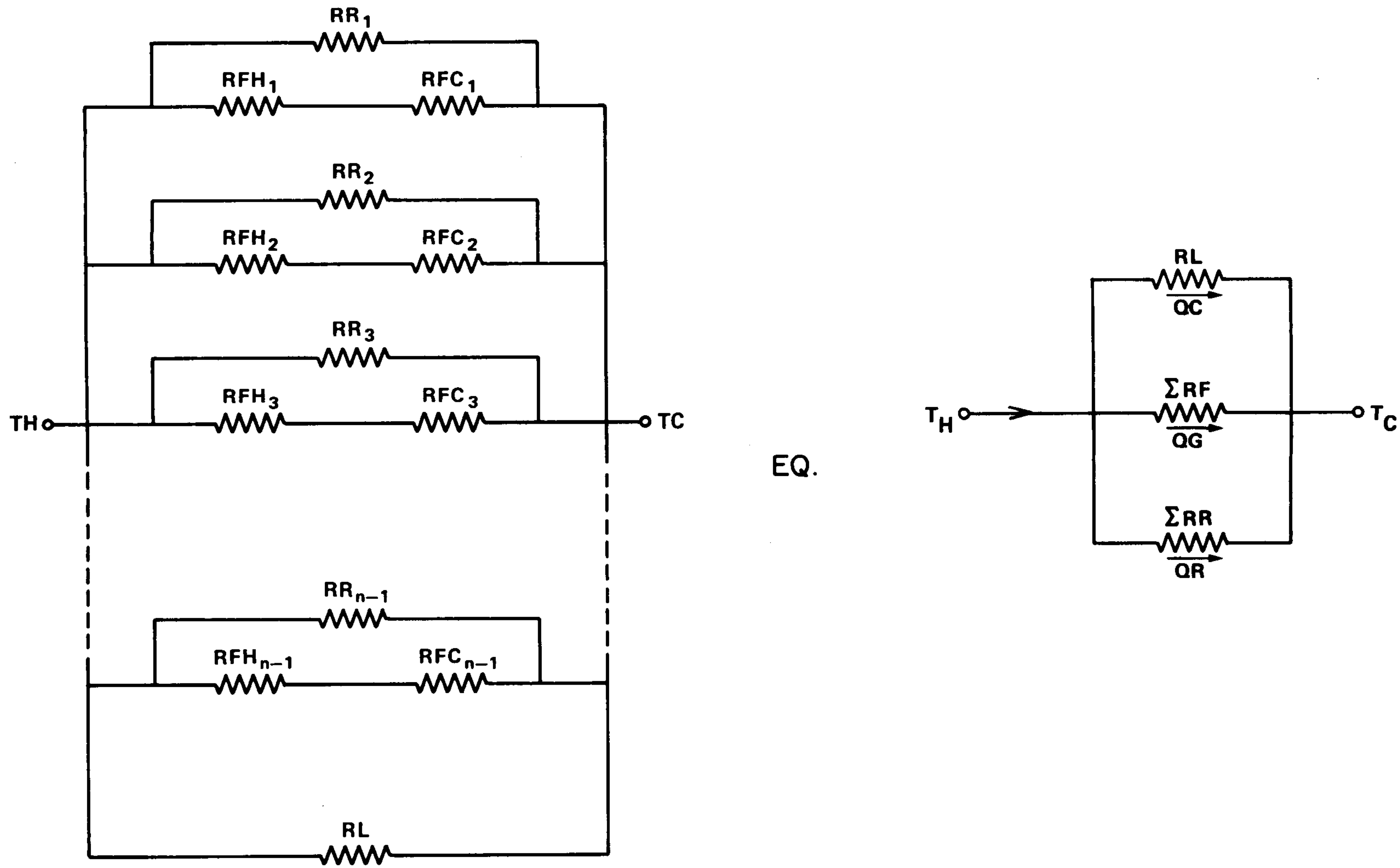

Figure A.2. Thermal Circuit

(4) a combination of QG, QR, and QL = Q.

are computed and printed out along with the temperatures on the hot side (THF) and on the cold side (TCF). The following ratios are then computed:

QRG = QG/Q
QRR = QR/Q
QRL = QL/Q

The program proceeds with the calculation for the conditions when the switch is off, where the same information is printed out as for the on mode. Finally, at the end of the program, the on conductance, the off conductance, and the switch ratio based on heat flow are printed out. At the conclusion, the user has the option to either run another case or terminate the program.

Table A.1. Program Listings of HTSWCH

```
      PROGRAM HTSWCH
C
C*********************** >>> PROGRAM HTSWCH <<< ************************
C*                                                                     *
C*                SWITCH DESIGN THEORY (FIN SHAPE CASE)                *
C*                  DESIGN CONCEPT BY : DR. C.K. CHAN                  *
C*                       PROGRAM BY : K.I.BOUDAIE                      *
C*                              (5/6/85)                               *
C*                                                                     *
C*     THIS PROGRAM CALCULATES THE HEAT TRANSFER RATE , THE  'ON', AND *
C* THE OFF CONDUCTANCES OF A FIN SHAPED HEAT SWITCH.                   *
C* ALL THE TEMPERATURE DEPENDENT PROPERTIES, SUCH AS THE THERMAL CONDU-*
C* CTIVITIES OF THE GAS,OF THE FIN AND OF THE SUPPORT MATERIAL, AND THE*
C* SURFACE EMISSIVITY IS INCORPORATED IN THIS PROGRAM.                 *
C*                                                                     *
C******************** >>> VARIABLE DECLARATION <<< *********************
C
      DIMENSION TKGHE(22),TKGH2(40),TKMCU(48),TKISS(24),TKIGS(48)
      DIMENSION TKIGT(28),RFH(24),RFC(24),RR(24),RG(24),XL(24),A(24)
      DIMENSION TKMCP(48),RF(24)
C
      REAL*8 D,DELTA,AN,PI,AC1,AC2,H,XKG1,P,BB,XKM2,XKM3,B,X,GAMA,RF
      REAL*8 RFH,RH,BB1,B1,X1,GAMA1,RFC,RL,XKI4,DELTAI,TAV1,TAV,TAV3
      REAL*8 SIGMA,RG,KG1,REQ1,REQ,Q,Q1,TCF,THF,QS,RC,P1,T,H1,TAV2,R
      REAL*8 GAMAHE,ALPHA1,AREA,RATIO,THN,XH,T1,QG,QT,QRG,QRR,QRL,TAVR
      REAL*8 QN,TCFN,THFN,DELTAF,TH,TC,AA,AASUM,REQR,REQFT,QL,QR,REQR1
      REAL*8 XMHE,XMH2,GAMAH2,XLF,XLS,TAV4,ASUM,THEDA,ARC,TRIANG,Y,Z
      REAL*8 TKGH2,TKGHE,TKMCU,TKMCP,TKISS,TKIGT,TKIGS,EPSON,ES,DIF,LIM
      INTEGER*2 I,J,K,L,M,N,NH,A1(24),A2(24)
      CHARACTER*10 XGAS,XMAT,XFIN
C
C*************** >>> TABLE OF THERMAL CONDUCTIVITIES <<< ****************
C*                              WATTS/CM-K                              *
C*                                                                      *
C*     TKGHE = GASEOUS HELIUM               TKIGS = GLASS               *
C*     TKGH2 = GASEOUS HYDROGEN             TKISS = STAINLESS STEEL     *
C*     TKMCU = HI-PUR. ANNLD. COPPER        TKIGT = GTEN                *
C*     TKMCP = O.F.H.C. COPPER                                          *
C*                                                                      *
C*    TABLE BY : J. E. JENSEN , "BUBBLE CHAMBER GROUP"                  *
C*                                                                      *
C************************************************************************
C
      DATA TKGHE / .109E-3,5.38,.183E-3,10.94,.23E-3,16.49,.277E-3,
     1             22.05,.322E-3,27.61,.363E-3,33.16,.692E-3,88.72,
     2             .95E-3,144.27, 1.16E-3,199.83,1.37E-3,255.38,
     3             1.73E-3,366.49/
C
      DATA TKGH2 / .045E-3,5.,.074E-3,10.,.155E-3,20.,.229E-3,30.,
     1     .298E-3,40.,.362E-3,50.,.422E-3,60.,.542E-3,80.,.664E-3,
     2     100.,.7905E-3,120.,.918E-3,140.,1.043E-3,160.,1.166E-3,
     3     180.,1.282E-3,200.,1.398E-3,220.,1.507E-3,240.,1.613E-3,
     4     260.,1.665E-3,270.,1.717E-3,280.,1.8165E-3,300./
C
      DATA TKMCU / 70.,4.,96.,6.,120.,8.,134.,10.,120.,15.,88.,20.,
     1     60.,25.,40.,30.,28.,35.,20.,40.,12.,50.,8.,60.,6.2,70.,
     2     5.7,76.,5.2,80.,4.7,90.,4.5,100.,4.3,120.,4.2,140.,4.1,
     3     160.,4.,180,4.,200.,4.,250.,4.,300./
C
```

```
      DATA TKMCP / 2.4,4.,3.7,6.,4.7,8., 6.0,10.,8.50,15.,11.,20.,
     1      12.,25.,12.,30.,11.,35.,10.0,40.,7.7,50.,6.2,60.,5.9,70.,
     2      5.2,76.,4.9,80.,4.7,90.,4.5,100.,4.3,120.,4.2,140.,4.1,
     3      160.,4.0,180,4.0,200.,4.0,250.,4.0,300./
C
      DATA TKIGS / .97E-3,4.,1.14E-3,6.,1.19E-3,8.,1.2E-3,10.,1.3E-3,
     1      15.,1.46E-3,20.,1.68E-3,25.,1.9E-3,30.,2.2E-3,35.,2.4E-3,
     2      40.,2.9E-3,50.,3.4E-3,60.,3.9E-3,70.,4.2E-3,76.,4.4E-3,80.,
     3      5.E-3,90.,5.5E-3,100.,6.4E-3,120.,7.3E-3,140.,7.9E-3,160.,
     4      8.5E-3,180.,9.E-3,200.,9.8E-3,250.,10.2E-3,300./
C
      DATA TKISS / 4.E-3,5.5,8.5E-3,10.,14.E-3,15.,21.E-3,20.,33.E-3,
     1      30.,41.E-3,40.,60.E-3,58.,70.E-3,80.,90.E-3,100.,130.E-3,
     2      150.,150.E-3,200.,160.E-3,300./
C
      DATA TKIGT / .5E-3,5.,1.E-3,10.,1.5E-3,20.,2.E-3,35.,2.25E-3,
     1      50.,2.5E-3,60.,2.75E-3,80.,3.E-3,95.,3.25E-3,115.,3.5E-3,
     2      135.,4.E-3,170.,4.5E-3,210.,4.75E-3,250.,5.E-3,300./
C
C     ASSIGN #1 TO THE CONSOLE & #2 TO THE PRINTER FOR OUTPUT
C
      OPEN (1,FILE = 'CON: ')
      OPEN (2,FILE = 'LPT1: ')
C
C*********************** >>> SET INITIAL VALUES <<< *********************
C*                                                                      *
C*    D       = FIN DIAMETER (cm)               XLS = SUPPROT LENGTH (cm) *
C*    DELTA   = GAP WIDTH (cm)                  XLF = FIN LENGTH (cm)     *
C*    DELTAI  = SUPPORT THICKNESS (cm)          N   = # OF FINS           *
C*    DELTAF  = FIN WIDTH (cm)                  ES  = EMISSIVITY          *
C*    TH      = HIGH TEMP. (ON MODE in K)       TC  = COLD TEMP (K)       *
C*    THN     = COLD TEMP. (OFF MODE in K)      P1  = OFF PRESSURE (Torr) *
C*                                                                      *
C***********************************************************************
C
      D = 5.08
      XLF = 2.54
      DELTA = 0.002 * 2.54
      XLS = XLF * 1.2
      PI = 3.141593
      DELTAI = 0.005464
      DELTAF = .3175
      N = D/DELTAF
      XMHE = 4.
      XMH2 = 2.
      GAMAHE = 1.67
      GAMAH2 = 1.4
      P1 = 1.E-6
      TH = 9.
      THN = 9.
      TC = 8.
      ES = 0.4
      EPSON = ES/(2.0-ES)
      SIGMA = 5.6693E-12*EPSON*4.0
      XGAS = 'HELIUM'
      XMAT = 'STEEL'
      XFIN = 'COPPERTP'
C
C********************* >>> INTERACTIVE ROUTINE <<< **********************
C
```

```
 5    WRITE (*,10) N,THN,D,TH,XLF,TC,XFIN,DELTAI,DELTAF,XLS,DELTA,
     1            XMAT,XGAS,P1,ES
 10   FORMAT (18X,'*****>>> SWITCH DESIGN THEORY <<<*****',////
     1 ' 1) NUMBER OF FINS =',I2,18X,' 8) HIGH TEMP (SWITCH=OFF) =',
     2 F7.2,' K'/' 2) DIAMETER =',F5.3,' CM',18X,' 9) HIGH TEMP (SWITCH=
     3 ON) =',F7.2,' K'/' 3) FIN LENGTH =',F5.3,' CM',15X,
     4 ' 10) LOW TEMPERATURE        =',F7.2,' K'/' 4) FIN MATERIAL = ',
     5 A10,10X,' 11) SUPPORT THICKNESS      =',E9.4,' CM'/
     6 ' 5) FIN WIDTH =',E9.4,' CM',12X,' 12) SUPPORT LENGTH        = '
     7 ,F5.3,' CM'/' 6) GAP WIDTH    =',E9.4,' CM',9X,' 13) MATERIAL  =
     8 ',A10/' 7) GAS IN THE GAP =',A10,9X,' 14) OFF PRESSURE       = '
     9 ,E9.3,' Torr'/39X,' 15) FIN"S EMISSIVITY = ',E9.3//)
C
      WRITE (*,15)
 15   FORMAT (' ARE YOU GOING TO USE THE ABOVE DEMENSIONS FOR THE '/
     1         ' DESIGN CALCULATIONS?(1=YES,0=NO)')
      READ (*,17) J1
 17   FORMAT (I3)
      IF (J1.EQ.1) GOTO 100
 210  WRITE (*,20)
 20   FORMAT (' THEN ENTER THE DIMENSION TO BE CHANGED(1 TO 16).'/
     1        ' (16 = REVIEW THE NEW LIST)')
      READ (*,23) J2
 23   FORMAT (I3)
      IF (J2.EQ.1) THEN
               WRITE (*,24)
 24            FORMAT (' NUMBER OF FINS IS DETERMINED BY THE DIAMETER'/
     1         ' AND/OR THE FIN WIDTH (CHOOSE 2 AND/OR 5).'/)
               GOTO 200
      ELSEIF (J2.EQ.2) THEN
               WRITE(*,26)
 26            FORMAT (' ENTER THE NEW VALUE FOR THE DIAMETER')
               READ (*,27) D
 27            FORMAT (F5.3)
               N = D/DELTAF
               NH = N/2
               XH = N/2.
               IF (NH.NE.XH) THEN
                   N = N-1
                   D = N*DELTAF
               ELSE
                   D = N*DELTAF
               ENDIF
               GOTO 200
      ELSEIF (J2.EQ.3) THEN
               WRITE (*,28)
 28            FORMAT (' ENTER THE NEW VALUE FOR THE FIN LENGHT')
               READ (*,30) XLF
 30            FORMAT (F5.3)
               GOTO 200
      ELSEIF (J2.EQ.6) THEN
               WRITE (*,31)
 31            FORMAT (' ENTER THE NEW VALUE FOR THE GAP WIDTH')
               READ (*,32) DELTA
 32            FORMAT (E10.4)
               GOTO 200
      ELSEIF (J2.EQ.7) THEN
               WRITE (*,33)
 33            FORMAT (' ENTER THE GAS USED (HELIUM OR HYDROGEN)')
               READ (*,34) XGAS
```

```
34          FORMAT (A10)
            GOTO 200
      ELSEIF (J2.EQ.13) THEN
            WRITE (*,35)
35          FORMAT (' ENTER THE MATERIAL USED (GLASS,STEEL,OR GTEN)')
            READ (*,36) XMAT
36          FORMAT (A10)
            GOTO 200
      ELSEIF (J2.EQ.8) THEN
            WRITE (*,37)
37          FORMAT (' ENTER THE NEW VALUE FOR TH (SWITCH OFF).')
            READ (*,38) THN
38          FORMAT (F7.3)
            GOTO 200
      ELSEIF (J2.EQ.9) THEN
            WRITE (*,40)
40          FORMAT (' ENTER THE NEW VALUE FOR TH (SWITCH ON).')
            READ (*,42) TH
42          FORMAT (F7.3)
            GOTO 200
      ELSEIF (J2.EQ.10) THEN
            WRITE (*,44)
44          FORMAT (' ENTER THE VALUE FOR TC.')
            READ (*,45) TC
45          FORMAT (F7.3)
            GOTO 200
      ELSEIF (J2.EQ.11) THEN
            WRITE (*,46)
46          FORMAT (' WHAT IS THE SUPPORT THICKNESS?')
            READ (*,47) DELTAI
47          FORMAT (E9.3)
            GOTO 200
      ELSEIF (J2.EQ.12) THEN
            WRITE (*,48)
48          FORMAT (' WHAT IS THE SUPPORT LENGTH?')
            READ (*,49) XLS
49          FORMAT (F5.3)
            GOTO 200
      ELSEIF (J2.EQ.5) THEN
            WRITE (*,50)
50          FORMAT (' ENTER THE NEW VALUE OF THE FIN WIDTH')
            READ (*,51) DELTAF
51          FORMAT (E9.3)
            N = D/DELTAF
            NH = N/2
            XH = N/2.
            IF (NH.NE.XH) THEN
                N = N-1
                D = N*DELTAF
            ELSE
                D = N*DELTAF
            ENDIF
            GOTO 200
      ELSEIF (J2.EQ.14) THEN
            WRITE (*,52)
52          FORMAT (' ENTER THE NEW VALUE FOR THE OFF PRESSURE.')
            READ (*,53) P1
53          FORMAT (E9.3)
            GOTO 200
      ELSEIF (J2.EQ.4) THEN
```

```
              WRITE (*,54)
 54         FORMAT (' ENTER THE FIN MATERIAL USED (COPPER OR COPPERTP)')
 55           READ (*,56) XFIN
 56           FORMAT (A10)
              IF (XFIN.EQ.'COPPER' .OR. XFIN.EQ.'COPPERTP') THEN
              GOTO 200
              ELSE
              WRITE (*,57) XFIN
 57           FORMAT (A10,' IS NOT ACCEPTABLE (COPPER OR COPPERTP)')
              GOTO 55
              ENDIF
      ELSEIF (J2.EQ.15) THEN
              WRITE (*,58)
 58           FORMAT (' ENTER THE FIN"S EMISSIVITY.')
              READ (*,59) ES
 59           FORMAT (E9.3)
              EPSON = ES/(2.0-ES)
              SIGMA = 5.6693E-12*EPSON*4.0
              GOTO 200
      ELSEIF (J2.EQ.16) THEN
              GOTO 5
      ELSE
              WRITE (*,60)
 60           FORMAT (' ONLY NUMBERS 1-->16 ARE ACCEPTABLE.'//)
      ENDIF
C
 200  WRITE(*,61)
 61   FORMAT (' ANY MORE CHANGES?(1=YES,0=NO)')
      READ (*,62) J3
 62   FORMAT (I3)
      IF (J3.EQ.1) GOTO 210
C
C*********************** >>> THE MAIN PROGRAM <<< ***********************
C
 100  WRITE (1,110) N,THN,D,TH,XLF,TC,XFIN,DELTAI,DELTAF,XLS,DELTA,
     1              XMAT,XGAS,P1,ES
      WRITE (2,110) N,THN,D,TH,XLF,TC,XFIN,DELTAI,DELTAF,XLS,DELTA,
     1              XMAT,XGAS,P1,ES
 110  FORMAT (18X,'*****>>> SWITCH DESIGN THEORY <<<*****',////
     1 ' 1) NUMBER OF FINS =',I2,18X,' 8) HIGH TEMP (SWITCH=OFF) =',
     2 F7.2,' K'/' 2) DIAMETER =',F5.3,' CM',18X,' 9) HIGH TEMP (SWITCH=
     3 ON) =',F7.2,' K'/' 3) FIN LENGTH =',F5.3,' CM',15X,
     4 ' 10) LOW TEMPERATURE =',F7.2,' K'/' 4) FIN MATERIAL = ',A10,
     5 10X,' 11) SUPPORT THICKNESS =',E9.4,' CM'/
     6 ' 5) FIN WIDTH =',E9.4,' CM',12X,' 12) SUPPORT LENGTH = ',F5.3,
     7 ' CM'/' 6) GAP WIDTH    =',E9.4,' CM',9X,' 13) MATERIAL  = ',A10/
     8 ' 7) GAS IN THE GAP = ',A10,8X,' 14) OFF PRESSURE =',E9.3,' Torr'
     9 /39X,' 15) FIN"S EMISSIVITY = ',E9.3//)
C
C**************************** >>> ON MODE <<< **************************
C
      THF = TH
      TCF = TC
      TAV1 = (THF+TCF)/2.
      TAV2 = (TH+THF)/2.
      TAV3 = (TCF+TC)/2.
      TAV4 = (TH+TC)/2.
      TAVR = (TH+TC)*(TH*TH+TC*TC)/4.0
      DATA K1/1/,K2/1/,K3/1/,K4/1/
      DATA N1/11/,N2/24/,N3/24/,N4/24/,N5/20/,N6/12/,N7/14/
```

```
C
C*************** >>> INTERPOLATE THERMAL CONDUCTIVITIES <<< **************
C
      IF (XGAS.EQ.'HELIUM') THEN
          XKG1 = POLATE (TKGHE,TAV1,N1,K1)
      ELSEIF (XGAS.EQ.'HYDROGEN') THEN
          XKG1 = POLATE (TKGH2,TAV1,N5,K1)
      ELSE
      WRITE (1,115) XGAS
      WRITE (2,115) XGAS
 115  FORMAT (A10,' IS NOT ACCEPTABLE, CALCULATIONS CANCELLED!'/'1')
      GOTO 5
      ENDIF
 120  IF (XFIN.EQ.'COPPER') THEN
          XKM2 = POLATE (TKMCU,TAV2,N2,K2)
          XKM3 = POLATE (TKMCU,TAV3,N3,K3)
      ELSE
          XKM2 = POLATE (TKMCP,TAV2,N2,K2)
          XKM3 = POLATE (TKMCP,TAV3,N3,K3)
      ENDIF
      IF (XMAT .EQ. 'STEEL') THEN
          XKI4 = POLATE (TKISS,TAV4,N6,K4)
      ELSEIF (XMAT.EQ.'GLASS') THEN
          XKI4 = POLATE (TKIGS,TAV4,N4,K4)
      ELSEIF (XMAT.EQ.'GTEN') THEN
          XKI4 = POLATE (TKIGT,TAV4,N7,K4)
      ELSE
      WRITE (1,122) XMAT
      WRITE (2,122) XMAT
 122  FORMAT (A10,' IS NOT ACCEPTABLE. CALCULATIONS CANCELLED!'/'1')
      GOTO 5
      ENDIF
C
C*************** >>> CALCULATING FIN LENGHTS AND AREAS <<< ***************
C*                           IN CM AND CM**2                              *
C*                                                                        *
C*   R      = HEAT SWITCH RADIUS              AASUM = TOTAL CONDUCTION AREA   *
C*   XL(I) = FIN LENGHT                       A(I)   = CONDUCTION AREA        *
C*                                                                        *
C*************************************************************************
C
      NH = N/2
      R = D/2.
      AASUM = 0.
      ASUM = 0.0
C
      WRITE (2,900)
 900  FORMAT (' NH',7X,' Wf(cm)',4X,' A=Lf*Wf(cm^2)',4X,' AC(cm^2)'/)
      DO 300 I = 1,NH
             T1 = (NH -I)*DELTAF
             XL(I) = 2. * SQRT(R**2. - T1**2.)
             THEDA = 2. * ACOS(T1/R)
             ARC = (R**2.)*THEDA/2.
             TRIANG = 0.5*T1*XL(I)
             A(I) = ARC - TRIANG
             A(I) = A(I) - ASUM
             ASUM = A(I) + ASUM
             A(N-I+1) = A(I)
             XL(N-I) = XL(I)
             AA = XL(I)*XLF
```

```
             AASUM = AASUM + 2*AA
             WRITE (2,950) I,XL(I),AA,A(I)
 950         FORMAT (I2,3(5X,F10.4))
 300   CONTINUE
C
       AASUM = AASUM - AA
       WRITE (2,315) AASUM
 315   FORMAT (/6X,' TOTAL AREA =',F9.4,'  cm^2'/)
C
C**************** >>> INDEXING THE FINS (COLD & HOT) <<< ******************
C*                                                                       *
C*   A1(L) = AREA OF THE HOTSIDE                                         *
C*   A2(L) = AREA OF THE COLDSIDE                                        *
C*                                                                       *
C*************************************************************************
C
       L = 2
       DO 310  K = 3,N,2
             A1(L) = K
             A2(L) = K-1
             L = L+1
             A1(L) = K
             A2(L) = K+1
             L = L+1
 310   CONTINUE
C
C****************** >>>  CALCULATING THE RESISTANCES <<< *****************
C*                                'ON MODE'                              *
C*                RESISTANCE IN K/W & HEAT FLOW IN WATTS                 *
C*                                                                       *
C* RFH = THERMAL RESISTEANCE (HOT FIN)    Q     = TOTAL HEAT FLOW        *
C* RFC = THERMAL RESISTANCE (COLD FIN)    QL    = HEAT FLOW (SUPPORT)    *
C* RR  = THERMAL RESISTANCE (RADIATION)   QR    = HEAT FLOW (RADIATION)  *
C* RG  = THERMAL RESISTANCE (GAS)         QG    = HEAT FLOW (HEAT SWITCH) *
C* REQ = TOTAL RESISTANCE               REQFT = TOTAL FIN RESISTANCE     *
C* REQR= TOTAL RADIATION RESISTANCE     SIGMA = STEFAN-BOLTZMAN CONST.   *
C* P   =  FIN PERIMETER (cm)                     (W / cm^2 K^4)          *
C*                                                                       *
C*************************************************************************
C
       REQR = 0.0
       REQFT = 0.0
       L = 0
       M = 0
       DO 320 J = 1,N-1
             IF (J.EQ.1) THEN
                 AC1 = A(J)
                 AC2 = A(J+1)/2.
             ELSEIF (J.EQ.N-1) THEN
                 AC2 = A(N)
                 AC1 = A(N-1)/2.
             ELSE
                 L = A1(J)
                 AC1 = A(L)/2.
                 M = A2(J)
                 AC2 = A(M)/2.
             ENDIF
          H = (2.*XKG1)/DELTA
          P = XL(J)
          BB = H*P/(XKM2*AC1)
```

```
          B = SQRT(BB)
          X = B*XLF
          GAMA = (1./(B*XLF))*DTANH(X)
          RFH(J) = 1./(H*P*XLF*GAMA)
C
          BB1 = H*P/(XKM3*AC2)
          B1 = SQRT(BB1)
          X1 = B1*XLF
          GAMA1 = (1./(B1*XLF))*DTANH(X1)
          RFC(J) = 1./(H*P*XLF*GAMA1)
C
          RR(J) = 1./(SIGMA*XL(J)*XLF*TAVR)
          RG(J) = DELTA/(XKG1*XL(J)*XLF)
C
          REQR1 = 1./RR(J)
          REQR = REQR + REQR1
          RF(J) = RFH(J) + RFC(J)
          REQFT = REQFT + (1./RF(J))
 320  CONTINUE
C
      RL = XLS/(XKI4*PI*D*DELTAI)
      REQ1 = 1./RL + REQR +REQFT
      REQ = 1./REQ1
      REQR= 1./REQR
      REQFT=1./REQFT
C
      Q  = (TH-TC)/REQ
      QL = (TH-TC)/RL
      QR = (TH-TC)/REQR
      QG = (TH-TC)/REQFT
      QT = QR+QG+QL
C
C     COMPARE Q WITH QT AS A DOUBLE CHECK FOR EQUALITY
C
      DIF = ABS(Q-QT)
      LIM = 0.005*QT
      IF (DIF .GE. LIM) THEN
            WRITE (1,322) QT,Q
            WRITE (2,322) QT,Q
 322        FORMAT (1X,' QT = ',E12.7,'  WHICH IS NOT EQUAL TO ',
     1                1X,' Q = ',E12.7 /)
      ENDIF

      QRG = QG/QT
      QRR = QR/QT
      QRL = QL/QT
C
C****************** >>> PRINT OUT RESULTS (ON MODE) <<< *****************
C
      WRITE (2,140) XKG1,XKM2,XKM3,XKI4
      WRITE (1,140) XKG1,XKM2,XKM3,XKI4
 140  FORMAT (/,' SWITCH = ON:'//,3X,' Kg',8X,' KmH',8X,' KmC',8X,
     1        ' KL',8X,'(W/cmK)'/1X,E9.4,3(3X,E9.4)///3X,' RFH',8X,
     2        ' RFC',8X,'RF',8X,' RR',9X,' RG',9X,' RL',8X,' (K/W)'/)
C
      DO 150 L=1,N-1
             WRITE (2,145) RFH(L),RFC(L),RF(L),RR(L),RG(L),RL
             WRITE (1,145) RFH(L),RFC(L),RF(L),RR(L),RG(L),RL
 145         FORMAT (1X,E9.4,5(3X,E9.4))
 150  CONTINUE
```

```
      WRITE (2,155)
      WRITE (1,155)
 155  FORMAT (// ,1X,' THF(K)',5X,' TCF(K)',6X,' QG(W)',4X,
     1        ' QR(W)',5X,' QL(W)',5X,' Q(W)' )
C
      WRITE (2,160) THF,TCF,QG,QR,QL,QT,QRG,QRR,QRL
      WRITE (1,160) THF,TCF,QG,QR,QL,QT,QRG,QRR,QRL
 160  FORMAT (1X,E9.4,5(2X,E9.4)/ 26X,' QRG',6X,' QRR',7X,' QRL'/
     1       23X,E9.4,2(2X,E9.4)/'1' )
C
C*************************** >>> OFF MODE <<< *************************
C
      DATA K1/1/,K2/1/,K3/1/,K4/1/
      THFN = THN
      TCFN = TC
      TAV1 = (THFN+TCFN)/2.
      TAV2 = (THN+THFN)/2.
      TAV3 = (TCFN+TC)/2.
      TAV4 = (THN+TC)/2.
      TAVR = (THN+TC)*(THN*THN+TC*TC)/4.0
C
C*************** >>> INTERPOLATE THERMAL CONDUCTIVITIES <<< **************
C
      IF (XFIN.EQ.'COPPER') THEN
          XKM2 = POLATE (TKMCU,TAV2,N2,K2)
          XKM3 = POLATE (TKMCU,TAV3,N3,K3)
      ELSE
          XKM2 = POLATE (TKMCP,TAV2,N2,K2)
          XKM3 = POLATE (TKMCP,TAV3,N3,K3)
      ENDIF
      IF (XMAT .EQ. 'STEEL') THEN
          XKI4 = POLATE (TKISS,TAV4,N6,K4)
      ELSEIF (XMAT.EQ.'GLASS') THEN
          XKI4 = POLATE (TKIGS,TAV4,N4,K4)
      ELSE
          XKI4 = POLATE (TKIGT,TAV4,N7,K4)
      ENDIF
C
C***************** >>>  CALCULATING THE RESISTANCES <<< *****************
C*                             'OFF MODE'                                *
C*                 RESISTANCE IN K/W & HEAT FLOW IN WATTS                *
C*                                                                       *
C* RFH = THERMAL RESISTEANCE (HOT FIN)      Q     = TOTAL HEAT FLOW       *
C* RFC = THERMAL RESISTANCE (COLD FIN)      QL    = HEAT FLOW (SUPPORT)   *
C* RR  = THERMAL RESISTANCE (RADIATION)     QR    = HEAT FLOW (RADIATION) *
C* RG  = THERMAL RESISTANCE (GAS)           QG    = HEAT FLOW (HEAT SWITCH) *
C* REQ = TOTAL RESISTANCE                 REQFT = TOTAL FIN RESISTANCE    *
C* REQR= TOTAL RADIATION RESISTANCE       SIGMA = STEFAN-BOLTZMAN CONST.  *
C* P   =  FIN PERIMETER (cm)                      (W /cm^2 K^4)           *
C*                                                                       *
C************************************************************************
C
      REQR = 0.0
      REQFT= 0.0
      L = 0
      K = 0
C
      IF (XGAS.EQ.'HELIUM') GOTO 280
         XM = XMH2
         XGAMA = GAMAH2
```

```
      IF (TAV1.GT.50.) GOTO 250
         ALPHA1 = 1.
         GOTO 260
 250  CONTINUE
      ALPHA1 = 0.5
      GOTO 260
 280  CONTINUE
         XM = XMHE
         XGAMA = GAMAHE
      IF (TAV1.GT.50.) GOTO 270
      IF (TAV1.GT.12) GOTO 272
         ALPHA1 = 1.
         GOTO 260
 270  CONTINUE
      ALPHA1 = 0.4
      GOTO 260
 272  CONTINUE
      ALPHA1 = .6
 260  ALPHA = ALPHA1/(2.-ALPHA1)
      T = SQRT(TAV1)
      H1 = (0.2426/SQRT(XM))*ALPHA*((XGAMA+1)/(XGAMA-1))*(P1/T)
C
      DO 400 M = 1,N-1
           IF (M.EQ.1) THEN
               AC1 = A(M)
               AC2 = A(M+1)/2.
           ELSEIF (M.EQ.N-1) THEN
               AC2 = A(N)
               AC1 = A(N-1)/2.
           ELSE
               L = A1(M)
               AC1 = A(L)/2.
               K = A2(M)
               AC2 = A(K)/2.
           ENDIF
        AREA = XLF * XL(M)
        RG(M) = 1./(H1*AREA)
        XKG1 = DELTA/(RG(M)*XL(M)*XLF)
C
        H = (2.*XKG1)/DELTA
        P = XL(M)
        BB = H*P/(XKM2*AC1)
        B = SQRT(BB)
        X = B*XLF
        GAMA = (1./(B*XLF))*DTANH(X)
        RFH(M) = 1./(H*P*XLF*GAMA)
C
        BB1 = H*P/(XKM3*AC2)
        B1 = SQRT(BB1)
        X1 = B1*XLF
        GAMA1 = (1./(B1*XLF))*DTANH(X1)
        RFC(M) = 1./(H*P*XLF*GAMA1)
C
        RR(M) = 1./(SIGMA*XL(M)*XLF*TAVR)
C
        REQR1 = 1./RR(M)
        REQR = REQR + REQR1
        REQ12 = RFH(M) + RFC(M)
        RF(M) = RFH(M) + RFC(M)
        REQFT = REQFT + (1./RF(M))
```

```
 400  CONTINUE
C
      RL = XLS/(XKI4*PI*D*DELTAI)
      REQ1 = 1./RL + REQR +REQFT
      REQ = 1./REQ1
      REQR= 1./REQR
      REQFT=1./REQFT
C
      QN = (THN-TC)/REQ
      QL = (THN - TC)/RL
      QR = (THN-TC)/REQR
      QG = (THN-TC)/REQFT
      QT1 = QR+QG+QL
C
C     COMPARE Q WITH QT AS A DOUBLE CHECK FOR EQUALITY
C
      DIF = ABS(QN-QT1)
      LIM = 0.005*QT1
      IF (DIF .GE. LIM) THEN
            WRITE (1,408) QT1,QN
            WRITE (2,408) QT1,QN
 408        FORMAT (1X,' QT = ',E15.9,'  WHICH IS NOT EQUAL TO ',
     1                1X,' Q = ',E15.9 /)
      ENDIF
C
C****************** >>> PRINT OUT RESULTS (OFF MODE) <<< ******************
C
      WRITE (2,410) XKG1,XKM2,XKM3,XKI4
      WRITE (1,410) XKG1,XKM2,XKM3,XKI4
 410  FORMAT (//,' SWITCH = OFF:'//,3X,' Kg',8X,' KmH',8X,' KmC',8X,
     1         ' KL',8X,'(W/cmK)'/1X,E9.4,3(3X,E9.4)///3X,' RFH',8X,
     2         ' RFC',8X,' RF',8X,' RR',9X,' RG',9X,' RL',8X,' (K/W)'/)
C
      DO 430 LL=1,N-1
             WRITE (2,420) RFH(LL),RFC(LL),RF(LL),RR(LL),RG(LL),RL
             WRITE (1,420) RFH(LL),RFC(LL),RF(LL),RR(LL),RG(LL),RL
 420         FORMAT (1X,E9.4,5(3X,E9.4))
 430  CONTINUE
      WRITE (1,440)
      WRITE (2,440)
C
      QRG = QG/QT1
      QRR = QR/QT1
      QRL = QL/QT1
C
 440  FORMAT(///,2X,' THF(K)',4X,' TCF(K)',6X,' QG(W)',4X,
     1         ' QR(W)',5X,' QL(W)',5X,' Q(W)' )
      WRITE (1,445) THFN,TCFN,QG,QR,QL,QT1,QRG,QRR,QRL
      WRITE (2,445) THFN,TCFN,QG,QR,QL,QT1,QRG,QRR,QRL
 445  FORMAT (1X,E9.4,5(2X,E9.4)/ 26X,' QRG',6X,' QRR',7X,' QRL'/
     1        23X,E9.4,2(2X,E9.4) )
C
C****************** >>> PRINT OUT THE FINAL RESULT <<< *******************
C*                                                                       *
C*    XKON  = ON CONDUCTANCE (W/K)             RATIO = SWITCH RATIO      *
C*    XKOFF = OFF CONDUCTANCE (W/K)                                      *
C*                                                                       *
C*************************************************************************
C*
      XKON = Q/(TH-TC)
```

```
      XKOFF = QN  /(THN-TC)
      RATIO = QT/QT1
C
      WRITE (1,450) XKON,XKOFF,RATIO
      WRITE (2,450) XKON,XKOFF,RATIO
 450  FORMAT (////18X,' ***********************************'/
     1      18X,' *',32X,' *'/18X,' *  ON CONDUCTANCE  =',E9.3,
     2      ' W/K *'/18X,' *  OFF CONDUCTANCE =',E9.3,' W/K *'/
     3      18X,' *  SWITCH RATIO    = ',E9.4,'    *'/18X,' *',
     4      32X,' *'/18X,' ***********************************'/'1')
C
      WRITE (*,500)
 500  FORMAT (' RUN ANOTHER CASE ? (1=YES)')
      READ (*,505) J5
 505  FORMAT (I2)
      IF (J5.EQ.1) THEN
         GOTO 5
      ELSE
         GOTO 510
      ENDIF
 510  END
C
C**************** >>> SINGLE INTERPOLATION ROUTINE <<< ********************
C*                                                                       *
C*    XY  IS A TABLE OF Y(1),X(1),Y(2),X(2),........Y(NN),X(NN)          *
C*    XX  IS THE GIVEN VALUE FOR X                                       *
C*    NN  IS IS THE NUMBER OF PAIRS OF ENTERIES IN XY                    *
C*    KK  IS BOTH THE POSITION GUESS AND THE FINAL VALUE                 *
C*                                                                       *
C*************************************************************************
C*
      FUNCTION POLATE (XY,XX,NN,KK)
      DIMENSION XY(2)
      REAL*8 XY,XX,X
      INTEGER*2 NN,KK
      DATA ZERO/0.E0/,NERR/0/
C
      X = XX
      N = NN
      M = IABS(N)
      K = KK
      IF (K .LT. 1) THEN
                K = 1
      ELSEIF (K .GT. M) THEN
                K = M
      ENDIF
C
C     IS CONSTANT WANTED
C
      IF (M-1) 305,306,310
 305  POLATE = ZERRO
      RETURN
 306  POLATE = XY(1)
      RETURN
C
C     LOOP TO DECREASE THE INDEX
C
 310  IF (XY(2*K)-X) 320,320,311
 311  K = K - 1
      IF (K) 330,330,310
```

```
C
C     LOOP TO INCREASE INDEX
C
 320  IF (X-XY(2*K+2)) 400,400,321
 321  K = K + 1
      IF (K-M) 320,340,340
C
C     TEST FOR EXTRAPOLATION
C
 330  IF (N) 331,305,480
 331  K = 1
      GOTO 400
 340  IF (N) 341,305,490
 341  K = M - 1
C
C     GET ANSWER
C
 400  KK = K
      POLATE = XY(2*K-1) + (X-XY(2*K)) * (XY(2*K+1)-XY(2*K-1))
     1                                 / (XY(2*K+2)-XY(2*K))
      RETURN
C
C     POLATE FAILURE, SEARCH OUT OF BOUNDS
C
 480  POLATE = XY(1)
      GOTO 500
 490  POLATE = XY(2*M-1)
 500  NERR = NERR +1
      IF (NERR.GT.10) RETURN
      WRITE (2,510) KK,K,N,X,(XY(2*I),I=1,N)
      IF (NERR.EQ.10) THEN
                  WRITE (2,511)
      ENDIF
      RETURN
 510  FORMAT (16H1ERROR IN POLATE / 16H0INITIAL INDEX =,I6,10X,
     1 13HFINAL INDEX =,I6, 10X,14HARRAY LENGHT =,I6/ 10X,
     2 10HARGUMENT =, E14.6/ 20H0TABLE OF X VALUES = / (4E15.6))
 511  FORMAT (' ERROR PRINTOUT ON POLATE ERRORS ARE SUPPRESSED')
C
      RETURN
      END
C
C*****************************************************************************
```

Table A.2. HTSWCH Program Demonstration

*****>>> SWITCH DESIGN THEORY <<<*****

1) NUMBER OF FINS =16
2) DIAMETER =5.080 CM
3) FIN LENGTH =2.540 CM
4) FIN MATERIAL = COPPERTP
5) FIN WIDTH =.3175E+00 CM
6) GAP WIDTH =.5080E-02 CM
7) GAS IN THE GAP = HELIUM
8) HIGH TEMP (SWITCH=OFF) = 9.00 K
9) HIGH TEMP (SWITCH= ON) = 9.00 K
10) LOW TEMPERATURE = 8.00 K
11) SUPPORT THICKNESS =.1020E-01 CM
12) SUPPORT LENGTH = 3.800 CM
13) MATERIAL = STEEL
14) OFF PRESSURE = .100E-03 Torr
15) FIN"S EMISSIVITY = .400E+00

NH	Wf(cm)	A=Lf*Wf(cm^2)	AC(cm^2)
1	2.4593	6.2467	.5274
2	3.3601	8.5347	.9349
3	3.9656	10.0726	1.1685
4	4.3994	11.1745	1.3317
5	4.7093	11.9616	1.4489
6	4.9187	12.4935	1.5309
7	5.0402	12.8020	1.5832
8	5.0800	12.9032	1.6087

TOTAL AREA = 159.4742 cm^2

SWITCH = ON:

Kg	KmH	KmC	KL	(W/cmK)
.1505E-03	.5350E+01	.4700E+01	.7000E-02	

RFH	RFC	RF	RR	RG	RL	(K/W)
.2995E+01	.3076E+01	.6071E+01	.4582E+08	.5403E+01	.3335E+04	
.2241E+01	.2348E+01	.4589E+01	.3354E+08	.3954E+01	.3335E+04	
.1938E+01	.1937E+01	.3875E+01	.2842E+08	.3351E+01	.3335E+04	
.1722E+01	.1771E+01	.3494E+01	.2561E+08	.3020E+01	.3335E+04	
.1623E+01	.1639E+01	.3261E+01	.2393E+08	.2821E+01	.3335E+04	
.1545E+01	.1578E+01	.3123E+01	.2291E+08	.2701E+01	.3335E+04	
.1512E+01	.1535E+01	.3047E+01	.2236E+08	.2636E+01	.3335E+04	
.1499E+01	.1524E+01	.3023E+01	.2218E+08	.2616E+01	.3335E+04	
.1509E+01	.1538E+01	.3047E+01	.2236E+08	.2636E+01	.3335E+04	
.1551E+01	.1571E+01	.3122E+01	.2291E+08	.2701E+01	.3335E+04	
.1612E+01	.1651E+01	.3263E+01	.2393E+08	.2821E+01	.3335E+04	
.1741E+01	.1751E+01	.3491E+01	.2561E+08	.3020E+01	.3335E+04	
.1906E+01	.1973E+01	.3879E+01	.2842E+08	.3351E+01	.3335E+04	
.2305E+01	.2276E+01	.4581E+01	.3354E+08	.3954E+01	.3335E+04	
.3032E+01	.3034E+01	.6066E+01	.4582E+08	.5403E+01	.3335E+04	

THF(K)	TCF(K)	QG(W)	QR(W)	QL(W)	Q(W)
.9000E+01	.8000E+01	.4095E+01	.5572E-06	.2999E-03	.4095E+01
		QRG	QRR	QRL	
		.9999E+00	.1360E-06	.7322E-04	

SWITCH = OFF:

Kg	KmH	KmC	KL	(W/cmK)
.8423E-07	.5350E+01	.4700E+01	.7000E-02	

RFH	RFC	RF	RR	RG	RL	(K/W)
.4828E+04	.4828E+04	.9656E+04	.4582E+08	.9655E+04	.3335E+04	
.3534E+04	.3534E+04	.7068E+04	.3354E+08	.7067E+04	.3335E+04	
.2994E+04	.2994E+04	.5988E+04	.2842E+08	.5988E+04	.3335E+04	
.2699E+04	.2699E+04	.5398E+04	.2561E+08	.5397E+04	.3335E+04	
.2521E+04	.2521E+04	.5043E+04	.2393E+08	.5042E+04	.3335E+04	
.2414E+04	.2414E+04	.4828E+04	.2291E+08	.4828E+04	.3335E+04	
.2356E+04	.2356E+04	.4712E+04	.2236E+08	.4711E+04	.3335E+04	
.2337E+04	.2337E+04	.4675E+04	.2218E+08	.4674E+04	.3335E+04	
.2356E+04	.2356E+04	.4712E+04	.2236E+08	.4711E+04	.3335E+04	
.2414E+04	.2414E+04	.4828E+04	.2291E+08	.4828E+04	.3335E+04	
.2521E+04	.2521E+04	.5043E+04	.2393E+08	.5042E+04	.3335E+04	
.2699E+04	.2699E+04	.5398E+04	.2561E+08	.5397E+04	.3335E+04	
.2994E+04	.2994E+04	.5988E+04	.2842E+08	.5988E+04	.3335E+04	
.3534E+04	.3534E+04	.7067E+04	.3354E+08	.7067E+04	.3335E+04	
.4828E+04	.4828E+04	.9656E+04	.4582E+08	.9655E+04	.3335E+04	

THF(K)	TCF(K)	QG(W)	QR(W)	QL(W)	Q(W)
.9000E+01	.8000E+01	.2644E-02	.5572E-06	.2999E-03	.2944E-02
		QRG	QRR	QRL	
		.8980E+00	.1892E-03	.1018E+00	

```
***********************************
*                                 *
*  ON CONDUCTANCE  = .410E+01 W/K *
*  OFF CONDUCTANCE = .294E-02 W/K *
*  SWITCH RATIO    = .1391E+04    *
*                                 *
***********************************
```

APPENDIX B
ADPUMP: A PROGRAM TO DESIGN AN ADSORPTION PUMP

Interactive computer software was developed in Fortran 77 to model a gas sorption pump to be used with the non-mechanical gas gap heat switch. Heat switch geometry, gas volume, and the sorption materials are inputted in order to obtain the ideal pump geometry and switch-on energy. The program listing is presented in Table B.1 and it is executed by typing

B:> ADPUMP <RETURN>

The menu below appears on the screen. Only the choices between 14 and 18 can be altered at the present time. The gas could be either hydrogen or helium, while the material is copper.

```
                         ADSORPTION PUMP DESIGN

GIVEN PARAMETERS
HEAT SWITCH :
1)DIAMETER = .5080E+01 CM               4)GAP WIDTH = .5080E-02 CM
2)FIN AREA = .1595E+03 CM               5)BOTTOM GAP = .1016E-01 CM
3)SUPPORT TUBE LENGTH = .3810E+01       6)SIDE GAP = .1016E-01 CM

PUMP :
7)DIAMETER = .1384E+01 CM               15)HIGH TEMP. = .4000E+02 K
8)LENGTH = .3480E+01 CM                 16)LOW TEMP. = .7000E+01 K
9)WALL THICK. = .2032E+00 CM            17)HIGH PRESS. = .1000E+02 TORR
10)GAS LINE DIAMETER = .2921E+00 CM     18)LOW PRESS. = .1000E-05 TORR
11)GAS LINE LENGTH = .5715E+01 CM       19)GAS = HELIUM
12)MATERIAL = CU                        20)CHRCL DENS = .5000E+00 gr/cc
13)HEAT LINK RESISTANCE =               21)SOLID CHRCL DENS = .2000E+01 g/cc
   0000E+00 K/W                         22)ADSORP. MATERIAL = CHARCOAL
14)SINK TEMPERATURE = .8100E+01

ARE YOU GOING TO USE THE ABOVE DIMENSIONS FOR THE
DESIGN CALCULATIONS (1=YES)
```

After all parameters are inputted, the program proceeds with the calculation routine. The results of a sample run are shown in Table B.1.

Table B.1. Program Listing of ADPUMP

```
      PROGRAM ADPUMP
C
C************************** >>> PROGRAM ADPUMP <<< ***********************
C*                                                                       *
C*                     HEAT SWITCH PUMP DESIGN THEORY                    *
C*                    DESIGN CONCEPT BY : DR. C.K. CHAN                  *
C*                       PROGRAM BY : K.I. BOUDAIE                       *
C*                              (6/19/85)                                *
C*                                                                       *
C*    THIS INTERACTIVE PROGRAM IS TO MODEL A GAS SORPTION PUMP TO BE USED *
C* WITH NON MECHANICAL GAS GAP HEAT SWITCH.   HEAT SWITCH GEOMETRY,   GAS *
C* VOLUME,  AND THE SORPTION MATERIAL ARE INPUTTED IN ORDER TO OBTAIN THE *
C* IDEAL PUMP GEOMETRY AND SWITCH-ON ENERGY.                             *
C*                                                                       *
C********************** >>> VARIABLE DECLARATION <<< *********************
C
      DIMENSION TEMPHE(5),PRHE(7),VAHE(5,7),TEMPH2(5),PRH2(7),VAH2(5,7)
      DIMENSION TCPCU(12),TCPC(12),TUHE(12),TKMCU(48)
C
      REAL*8 X,Y,Z,XP,YP,ZP,A,B,OMA,OMB,TEMPHE,PRHE,VAHE,T,P,V,XLS
      REAL*8 TEMPH2,PRH2,VAH2,TCPCU,TCPC,VF,VB,VC,VL,DELTA,AREA,PI,D
      REAL*8 DELTAS,DELTAC,DL,XLL,TL,PL,VAL,CL,TH,PH,VAH,CH,XMHE,XMH2
      REAL*8 ROWL,R,ROWH,C,XMC,ROWP,ROWS,VP,AA,DP,XLP,XMP,ROWCU,TP
      REAL*8 CPC,TAV,CPCU,UH2,UHE,TUHE,QC,QA,QG,QCU,CPHE,CPH2,Q,PL1,PH1
      REAL*8 XLL1,DL1,VL1,AOL,A1,A2,XL1,XL2,VPP,VLT,RH,VH
      REAL*8 TKMCU,XKCU1,XKCU2,QLOSS,R1,R2,R3,REF,REQ,TS,TAV1,VT
      INTEGER*2 IXT,JYT,I,J,IP,IT,NT,NP,IT1,IP1,N1,K1,K2,K3,J1,J2,J3
      INTEGER*2 M1,M2,M3
      CHARACTER*10 XGAS
      CHARACTER*1 ANS
C
C*********************** >>> TABLE OF ARRAYS <<< *************************
C*                                                                       *
C* TEMPHE = HELIUM TEMPERATURE (K)       TEMPH2 = H2 TEMPERATURE (K)      *
C* PRHE   = HE PRESSURE (TORR)           PRH2 = H2 PRESSURE (TORR)        *
C* VAHE   = HE VOL. ADSORBED  (cc/g)     VAH2 = H2 VOL. ADSORBED  (cc/g)  *
C* TCPCU  = HEAT CAPACITY OF CU (J/g K)  TCPC = HEAT CAPACITY OF C (J/gK) *
C* TUHE   = HEAT OF ADSORP.,HE(J/MOLE)   TUH2 = HEAT OF ADSORP,H2(J/MOLE) *
C* TKMCU  = THEMAL CONDUCTIVITY OF CU (W/CM K)                           *
C*                                                                       *
C*************************************************************************
C
      DATA TEMPHE / 4.2,10.,15.,20.,80./
C
      DATA TEMPH2 / 20.,30.,40.,50.,80./
C
      DATA PRHE / -12.,-8.,-4.,-2.,-1.,0.,1./
C
      DATA PRH2 / -12.,-8.,-6.,-4.,-2.,0.,1./
C
      DATA VAHE / 150.,  5.,  0.,  0.,  0.,
     1            200., 25., 1.9,  0.,  0.,
     2            240.,100., 20., 3.8,  0.,
     3            250.,180., 60., 18.,  0.,
     4            255.,200.,100., 40.,  0.,
     5            260.,220.,150., 80.,  0.,
     6            270.,230.,190.,140., 14./
C
```

```
      DATA VAH2 /  80., 12., 1.5,  0.,  0.,
     1            170., 45.,  9., 1.8,  0.,
     2            200., 85., 25.,  6.,  0.,
     3            220.,150., 55., 20.,  0.,
     4            260.,200.,120., 60., 3.8,
     5            280.,250.,200.,160., 25.,
     6            280.,250.,210.,200., 55./
C
      DATA TCPCU  / 8.6E-4,10.,7.7E-3,20., 2.05E-1,80., 2.54E-1,100.,
     1              3.56E-1,200., 3.86E-1,300./
C
      DATA TCPC  / 5.E-4,10., 6.3E-3,20., 9.7E-2,80., 1.4E-1,100.,
     1             4.14E-1,200., 7.16E-1,300./
C
      DATA TUHE / 220.90,9.40, 287.5,12.99, 350.,16.16, 387.5,17.57,
     1            412.50,18.55, 450.,50./
C
      DATA TKMCU / 3.2,4.,4.8,6.,6.3,8.,7.8,10.,11.0,15.,13.,20.,
     1     14.,25.,14.,30.,13.,35.,11.5,40.,8.8,50.,7.,60.,5.9,70.,
     2     5.5,76.,5.2,80.,4.7,90.,4.5,100.,4.3,120.,4.2,140.,4.1,
     3     160.,4.,180,4.,200.,4.,250.,4.,300./
C
C ASSIGN #1 TO THE CONSOLE & #2 TO THE PRINTER FOR THE OUTPUT
C
      OPEN (1,FILE = 'CON: ')
      OPEN (2,FILE = 'LPT1: ')
C
C ********************** >>> SET INITIAL VALUES <<< **********************
C                                                                        *
C * AREA = FIN AREA (CM^2)                    D  = H.S. BASE DIAMETER (CM)  *
C * DELTA = GAP WIDTH (CM)                    TH = HIGH TEMPERATURE (K)     *
C * DELTAS = BOTTOM GAP (CM)                  TL = LOW TEMPERATURE (K)      *
C * DELTAC = SIDE GAP (CM)                    PH = HIGH PRESSURE (TORR)     *
C * ROWP    = CHARCOAL DENSITY (gr/cc)        PL = LOW PRESSURE (TORR)      *
C * ROWS    = SOLID CHARCOAL DENSITY(gr/cc)   XLS= SUPPORT LENGHT (CM)      *
C * ROWCU   = COPPER DENSITY (gr/cc)          XLL= GAS LINE LENGHT (CM)     *
C * DP      = PUMP DIAMETER (CM)              DL = GAS LINE DIAMETER (CM)   *
C*  TP      = PUMP WALL THICKNESS             XLL1=AUX. LINE LENGHT (CM)    *
C*  XL1,2   = HEAT LINK LENGHT (CM)           DL1 =AUX. LINE DIAM. (CM)     *
C*  A1,2    = HEAT LINK AREA (CM^2)           R  = UNIVESAL GAS CONST.      *
C*  XMHE   = MOLECULAR WEIGHT,HE (gm/g MOLE)       (CM^3 TORR/MOLE K)       *
C*  XMH2   = MOLECULAR WEIGHT,H2 (gm/g MOLE)  RH = DRILLED HOLE RADIUS(CM)  *
C*                                                                       *
C ************************************************************************
C
      PI = 3.14159
      NT = 5
      NP = 7
      IT = 1
      IP = 1
      IT1 = 1
      IP1 = 1
      AREA = 159.4742
      DELTA = .5080E-2
      D = 5.08
      DELTAS = .004*2.54
      DELTAC = .004*2.54
C
C     SEE EXPERIMENT #67
C
```

```
      TH = 40.
      TL = 7.0
      TS = 8.1
      PH = 10.
      PL = 1.E-6
      R = 82.06 * 760.
      XMHE = 4.003
      XMH2 = 2.016
      XLS = 3.81
      XLL = 5.715
      XLP = 3.4798
      DL = .2921
      XLL1 = (48.*2.54) + (2.*2.*2.54)
      DL1 = 0.07 *2.54
      DP = 1.3843
      TP = .2032
      XL1 = (3./4.)*2.54
      XL2 = 5. * 2.54
      A1 = PI * (((1./16.)*2.54)**2.)
      A2 = PI * (((1./40.)*2.54)**2.)
      ROWP = .5
      ROWS = 2.
      ROWCU = 8.94
      CPHE = 1.25*4.187
      CPH2 = 3.43*4.187
      XGAS = 'HELIUM'
      RH = ((1./16)/2.)*2.54
C
C********************* >>> INTERACTIVE PROGARAM <<< **********************
C
 95   WRITE (1,100) D,DELTA,AREA,DELTAS,XLS,DELTAC
 100  FORMAT (29X,' ADSORPTION PUMP DESIGN'/' GIVEN PARAMETERS'/
     1         ' HEAT SWITCH :'/
     2 ' 1)DIAMETER =',E9.4,' CM',20X,' 4)GAP WIDTH =',E9.4,' CM'/
     3 ' 2)FIN ARREA =',E9.4,' CM',19X,' 5)BOTTOM GAP =',E9.4,' CM'/
     4 ' 3)SUPPORT TUBE LENGHT =',E9.4,12X,' 6)SIDE GAP =',E9.4,' CM'/)
      WRITE (1,102) DP,TH,XLP,TL,TP,PH,DL,PL,XLL,XGAS,ROWP,REQ,ROWS
 102  FORMAT (/' PUMP :'/
     1 ' 7)DAIAMETER =',E9.4,' CM',19X,' 15)HIGH TEMP. =',E9.4,' K'/
     2 ' 8)LENGHT =',E9.4,' CM',22X' 16)LOW TEMP. =',E9.4,' K'/
     3 ' 9)WALL THICK. = ',E9.4,' CM',16X,' 17)HIGH PRESS. = ',E9.4,
     4 ' TORR'/' 10)GAS LINE DIAMETER =',E9.4,' CM',10X ,
     5 ' 18)LOW PRESS. =',E9.4,' TORR'/
     6 ' 11)GAS LINE LENGHT = ',E9.4,' CM',11X,' 19)GAS = ',A10/
     7 ' 12)MATERIAL = CU',28X,' 20)CHRCL. DENS. = ',E9.4,' gr/cc'/
     8 ' 13)HEAT LINK RESISTANCE = ',E9.4,' K/W',5X,
     9 ' 21)SOLID CHRCL. DEN.=',E9.4,'g/cc')
      WRITE (1,104) TS
 104  FORMAT (' 14)SINK TEMPERATURE = ',E9.4,13X,
     1  ' 22)ADSORP. MATERIAL = CHARCOAL'//)
C
      WRITE (*,110)
 110  FORMAT (' ARE YOU GOING TO USE THE ABOVE DIMENSIONS FOR THE'/
     1        ' DESIGN CALCULATIONS?(1=YES)')
      READ (*,115) J1
 115  FORMAT (I3)
      IF (J1 .EQ. 1) THEN
              GO TO 190
      ELSE
      GOTO 118
```

```
      ENDIF
C
 118  WRITE (*,120)
 120  FORMAT (' THEN ENTER THE DIMENSION TO BE CHANGED.(14-19)'/
     1        ' (23 = REVIEW THE TABLE)')
      READ (*,122) J2
 122  FORMAT (I3)
      IF (J2 .EQ. 14) THEN
           WRITE (*,123)
 123       FORMAT (' ENTER A VALUE FOR THE TSINK.')
           READ (*,124) TS
 124       FORMAT (F7.3)
           GOTO 180
      ELSEIF (J2 .EQ. 15) THEN
           WRITE (*,130)
 130       FORMAT (' ENTER A VALUE FOR THE THIGH.')
           READ (*,135) TH
 135       FORMAT (F7.3)
           GOTO 180
      ELSEIF (J2 .EQ. 16) THEN
           WRITE (*,140)
 140       FORMAT (' ENTER A VALUE FOR THE TLOW.')
           READ (*,145) TL
 145       FORMAT (F7.3)
           GOTO 180
      ELSEIF (J2 .EQ. 17) THEN
           WRITE (*,150)
 150       FORMAT (' ENTER A VALUE FOR THE PHIGH.')
           READ (*,155) PH
 155       FORMAT (F7.3)
           GOTO 180
      ELSEIF (J2 .EQ. 18) THEN
           WRITE (*,160)
 160       FORMAT (' ENTER A VALUE FOR THE PLOW.')
           READ (*,165) PL
 165       FORMAT (E8.3)
           GOTO 180
      ELSEIF (J2 .EQ. 19) THEN
           WRITE (*,170)
 170       FORMAT (' WHAT IS THE GAS USED?')
           READ (*,175) XGAS
 175       FORMAT (A10)
           GOTO 180
      ELSEIF (J2 .EQ. 23) THEN
           GOTO  95
      ELSE
C
           WRITE (*,178)
 178       FORMAT (' ONLY THE NUMBERS 14 TO 18 ARE VARIABLE VALUE!')
           GOTO 118
      ENDIF
C
 180  WRITE (*,182)
 182  FORMAT (' ANY MORE CHANGES?(1=YES)')
      READ (*,184) J3
 184  FORMAT (I3)
      IF (J3 .EQ. 1) THEN
          GOTO 118
      ENDIF
 190  CONTINUE
```

```
C
C***************** >>>  START OF THE MAIN PROGRAM <<< ********************
C*                      VOLUME IN cc & HEAT IN JOULS                      *
C*                                                                        *
C* VF = FIN GAP VOLUME                      ROWL = LOW GAS DENSITY        *
C* VB = TOP & BOTTOM VOLUME                 ROWH = HIGH GAS DENSITY       *
C* VC = CIRCUMFRENTIAL VOLUME               XMC  = MASS OF CHARCOAL(gr)   *
C* VL = LINE VOLUME                         VP   = PUMP GAS VOLUME        *
C* VL1= AUX. LINE VOLUME                    VLT  = TOTAL LINE VOLUME      *
C* CL = LOW ADSORPTION RATIO                V=VPP= PUMP VOLUME            *
C* CH = HIGH ADSORPTION RATIO               XLP  = PUMP LENGHT(CM)        *
C* C  = ADSORPTION DIFFERENTIAL             XMP  = PUMP MASS(gr)          *
C* UH2= H2 ADSORPTION POTENTIAL             UHE  = HE ADSORPTION POTENTIAL *
C* QC = CHARCOAL HEAT                       QA   = PHASE CHANGE HEAT      *
C* QG = GAS HEAT                            QCU  = STRUCTURAL HEAT        *
C* REQ= HEAT LINK RESISTANCE (W/K)          QLOSS= HEAT LOSS VIA LINK (W) *
C*                                                                        *
C************************************************************************
C
      DATA N1/6/, K1/1/, K2/1/, K3/1/
      TAV = (TH + TL)/2.
      T = TH - TL
      AA = (PI*DP**2.)/4.
C
      VPP = XLP * AA
      VF = AREA*DELTA
      VB = ((PI*D**2.)/4.)*DELTAS
      VC = PI*D*XLS*DELTAC
      VL = ((PI*DL**2.)/4.)*XLL
      VL1= ((PI*DL1**2.)/4.)*XLL1
      VLT = VL + VL1
      VH = (2.*2. + 0.09375*16)*2.54
      VH = PI*VH*RH**2.
      VT = VPP + VF + VB + VC + VLT + VH
C
      PL1 = DLOG10(PL)
      PH1 = DLOG10(PH)
C
      IF (XGAS.EQ.'HELIUM') THEN
          CALL POL2 (TEMPHE,PRHE,VAHE,NT,NP,TL,PL1,VAL,IT,IP)
          CL = (VAL/22400.)*XMHE
          CALL POL2 (TEMPHE,PRHE,VAHE,NT,NP,TH,PH1,VAH,IT1,IP1)
          CH = (VAH/22400.)*XMHE
          ROWL = (PL*XMHE)/(R*TL)
          ROWH = (PH*XMHE)/(R*TH)
          UHE = POLATE (TUHE,TAV,N1,K3)
          UHE = UHE * 4.187
C
      ELSE
          CALL POL2 (TEMPH2,PRH2,VAH2,NT,NP,TL,PL1,VAL,IT,IP)
          CL = (VAL/22400.)*XMH2
          CALL POL2 (TEMPH2,PRH2,VAH2,NT,NP,TH,PH1,VAH,IT1,IP1)
          CH = (VAH/22400.)*XMH2
          ROWL = (PL*XMH2)/(R*TL)
          ROWH = (PH*XMH2)/(R*TH)
          UH2 = 1648.*4.187/2.016
       ENDIF
C
      C = CL - CH
      XMC = ((VT)*(ROWH-ROWL))/(C-(((1./ROWP)-
```

```
     1                                  (1./ROWS))*(ROWH-ROWL)))
C
      VP = (VPP)-(XMC/ROWS)
      V = VPP
      XMP = ROWCU*((PI*XLP*DP*TP)+((2.*PI*TP*DP**2.)/4.))
C
      CPC = POLATE (TCPC,TAV,N1,K1)
      CPCU = POLATE (TCPCU,TAV,N1,K2)
C
C     WRITE (2,895) TH,PH,VAH,TL,PL,VAL
C     WRITE (*,895) TH,PH,VAH,TL,PL,VAL
C895  FORMAT (/' AT TH = ',E10.5,' AT PH =',E10.5,' VAH = ',E10.5/
C    1        ' AT TC = ',E10.5,' AT PL =',E10.5,' VAL = ',E10.5//)
C     WRITE (2,990) CPC,CPCU,UHE
C990  FORMAT (/' CPC = ',E9.3,' CPCU = ',E9.3,' UHE = ',E9.3/)
C
      IF (XGAS.EQ.'HELIUM') THEN
          QC = XMC*CPC*T
          QA = XMC*C*UHE
          QG = XMC*C*CPHE*T
          QCU = XMP*CPCU*T
      ELSE
          QC = XMC*CPC*T
          QA = XMC*C*UH2
          QG = XMC*C*CPH2*T
          QCU = XMP*CPCU*T
      ENDIF
C
      DATA M1/24/,M2/1/,M3/1/
      TAV1 = (TH +TS)/2.
      XKCU1 = POLATE (TKMCU,TH,M1,M2)
      XKCU2 = POLATE (TKMCU,TAV1,M1,M3)
      Q = QC+QA+QG+QCU
      R1 = XL1/(XKCU1*A1)
      R2 = XL2/(XKCU2*A2)
      R3 = R2
      REF = R2/2.
      REQ = R1 + REF
      QLOSS = (TH - TS)/REQ
C
C******************* >>> PRINTOUT THE RESULTS <<< ***********************
C
      WRITE (1,200) D,DELTA,AREA,DELTAS,XLS,DELTAC
      WRITE (2,200) D,DELTA,AREA,DELTAS,XLS,DELTAC
 200  FORMAT (29X,' ADSORPTION PUMP DESIGN'//' GIVEN PARAMETERS'//
     1        ' HEAT SWITCH :'//
     2 ' 1)DIAMETER =',E9.4,' CM',20X,' 4)GAP WIDTH =',E9.4,' CM'/
     3 ' 2)FIN ARREA =',E9.4,' CM',19X,' 5)BOTTOM GAP =',E9.4,' CM'/
     4 ' 3)SUPPORT TUBE LENGHT =',E9.4,12X,' 6)SIDE GAP =',E9.4,' CM'/)
      WRITE (1,205) DP,TH,XLP,TL,TP,PH,DL,PL,XLL,XGAS,ROWP,REQ,ROWS
      WRITE (2,205) DP,TH,XLP,TL,TP,PH,DL,PL,XLL,XGAS,ROWP,REQ,ROWS
 205  FORMAT (/' PUMP :'//
     1 ' 7)DAIAMETER =',E9.4,' CM',19X,' 15)HIGH TEMP. =',E9.4,' K'/
     2 ' 8)LENGHT =',E9.4,' CM',22X' 16)LOW TEMP. =',E9.4,' CM'/
     3 ' 9)WALL THICK. = ',E9.4,' CM',16X,' 17)HIGH PRESS. = ',E9.4,
     4 ' TORR'/' 10)GAS LINE DIAMETER =',E9.4,' CM',10X ,
     5 ' 18)LOW PRESS. =',E9.4,' TORR'/
     6 ' 11)GAS LINE LENGHT = ',E9.4,' CM',11X,' 19)GAS = ',A10/
     7 ' 12)MATERIAL = CU',28X,' 20)CHARCOAL DENSITY = ',E9.4,' gr/cc'/
     8 ' 13)HEAT LINK RESISTANCE = ',E9.4,' K/W',5X,
```

```
    9 ' 21)SOLID CHRCL. DENS. = ',E9.4,' gr/cc')
      WRITE (1,210) TS
      WRITE (2,210) TS
 210  FORMAT (' 14)SINK TEMPERATURE = ',E9.4,13X,
     1  ' 22)ADSORP. MATERIAL = CHARCOAL'///)
C
      WRITE (1,215) VC,CL,VB,CH,VF,C,VL,QA,VPP,QCU,VP,QC,ROWL,QG,ROWH,
     1              XMP
      WRITE (2,215) VC,CL,VB,CH,VF,C,VL,QA,VPP,QCU,VP,QC,ROWL,QG,ROWH,
     1              XMP
 215  FORMAT (35X,' OUTPUT'///4X,' GAS VOLUME IN cc',23X,' HEAT IN JOULS
     1'//4X,' CIRCUMFERENTIAL GAP = ',E9.4,8X,
     2 ' LOW  ADSORPTION RATIO = ',E9.4/4X,' TOP & BOTTOM GAPS = ',
     3 E9.4,10X,' HIGH ADSORPTION RATIO = ',E9.4/4X,' FIN GAP = '
     4 ,E9.4,20X,' ADSORPTION RATIO = ',E9.4/4X,' LINE VOLUME = ',E9.4,
     5 16X,' DESORPTION HEAT = ',E9.4/4X,' PUMP VOLUME = ',E9.4,16X,
     6 ' STRUCTURAL HEAT = ',E9.4/4X,' PUMP GAS VOLUME = ',E9.4,12X,
     7 ' CHARCOAL HEAT = ',E9.4/4X,' LOW GAS DENSITY = ',E9.4,' cc/g',
     8 7X,' GAS HEAT = ',E9.4/4X,' HIGH GAS DENSITY = ',E9.4,' cc/g'6X,
     9 ' MASS OF PUMP =  ',E9.4,1X,' gr.'/////)
C
      WRITE (1,220) VT,XMC,Q,QLOSS
      WRITE (2,220) VT,XMC,Q,QLOSS
 220  FORMAT (19X,' *************************************'/
     1         19X,' *                                   *'/
     2         19X,' *   TOTAL VOLUME   = ',E9.4,1X,' cc ',' *'/
     3         19X,' * MASS OF CHARCOAL = ',E9.4,1X,' gr.',' *'/
     4         19X,' * SWITCH UP ENERGY = ',E9.4,1X,'  J ',' *'/
     5         19X,' *   HEAT  LOSS     = ',E9.4,1X,'  W ',' *'/
     6         19X,' *                                   *'/
     7         19X,' *************************************'//'1')
C
C     WRITE (2,225)
C     WRITE (*,225)
C225  FORMAT (' ALL LENGHTS ARE IN CM, PRESSURE IN TORR, DENSITY IN',
C    1         1X,' gr/cc, VOLUME IN cc,'/' AND HEAT IN JOULES'/'1')
C
      WRITE (*,230)
 230  FORMAT (/' ANY MORE RUNS? (YES OR NO) ')
      READ (*,235) ANS
 235  FORMAT (A1)
      IF (ANS .EQ. 'Y') THEN
                     GOTO 95
      ENDIF
      END
C
C *********************** >>> SUBROUTINE POL2 <<< ***********************
C *                                                                     *
C *   GENERAL ROUTINE TO INTERPOLATE A FUNCTION OF 2 VARIABLES          *
C *                                                                     *
C *   X     = TABLE OF FIRST VARIABLE                                   *
C *   Y     = TABLE OF SECOND VARIABALE                                 *
C *   Z     = TABLE OF FUNCTIONAL VALUES                                *
C *   IXT   = TOTAL NUMBER OF VALUES IN THE FIRST TABLE                 *
C *   JYT   = TOTAL NUBBER OF VALUES IN THE SECOND TABLE                *
C *   XP    = GIVEN VALUE OF THE FIRST VALUE                            *
C *   YP    = GIVEN VALUE OF THE SECOND VALUE                           *
C *   ZP    = INTERPOLATEF FUNCTIONAL VALUE                             *
C *   I     = INDEX FOR INITIAL GUESS AND FINAL POSITION OF VAR. 1      *
C *   J     = INDEX FOR INITIAL GUESS AND FINAL POSITION OF VAR. 2      *
```

```
C *                                                                          *
C ****************************************************************************
C
C      DETERMINE THE INDECIES FOR X AND Y TABLES
C
      SUBROUTINE POL2(X,Y,Z,IXT,JYT,XP,YP,ZP,I,J)
      DIMENSION X(IXT),Y(JYT),Z(IXT,JYT)
      INTEGER*2 IXT,JYT,I,J
      REAL*8 X,Y,Z,XP,YP,ZP,A,B,OMA,OMB
      DATA ONE/ 1./
C
C     WRITE (2,5) X(1),Y(1),Z(1,1),IXT,JYT,XP,YP,ZP,I,J
C5    FORMAT (' X(1),Y(1),Z(1,1),IXT,JYT,XP,YP,ZP,I,J='/
C    1          3(F6.2,3X),2I5,3(F6.2,3X),2I5/)
 10   IF (XP.LE.X(I+1)) GO TO 20
      I = I + 1
      IF (I.GE.IXT) GO TO 30
      GO TO 10
 20   CONTINUE
 22   IF (XP.GE.X(I)) GO TO 30
      I = I - 1
      IF (I.LT.1) GO TO 30
      GO TO 22
C
 30   CONTINUE
 32   IF (YP.LE.Y(J+1)) GO TO 40
      J = J + 1
      IF (J.GE.JYT) GO TO 60
      GO TO 30
 40   CONTINUE
 42   IF (YP.GE.Y(J)) GO TO 50
      J = J - 1
      IF (J.LT.1) GO TO 60
      GO TO 42
C
C     CALCULATE THE INTERPOLATED VALUE
C
 50   CONTINUE
      IF (I.LT.1 .OR. I.GE.IXT) GO TO 60
      A = (XP - X(I))/(X(I+1) - X(I))
      B = (YP - Y(J))/(Y(J+1) - Y(J))
      OMA = ONE - A
      OMB = ONE - B
      ZP = OMA*OMB*Z(I,J) + B*OMA*Z(I,J+1) + A*OMB*Z(I+1,J) +
     1     A*B*Z(I+1,J+1)
C     WRITE (2,51) I,J,X(I),Y(J),Z(I,J),ZP
C51   FORMAT (' I,J,X(I),Y(J),Z(I,J),ZP'/2I5,4(F8.3))
      RETURN
C
C     ERROR MESSAGE
C
 60   CONTINUE
      WRITE (2,70) I,XP,X(1),X(IXT),IXT,J,YP,Y(1),Y(JYT),JYT
 70   FORMAT (5X,' ERROR IN POL2. TABLE LIMIT EXCEEDED'/
     1 '   RESP. VALUES OF I, XP, X(1), X(IXT), IXT ='/9X,I5,3F9.4,I8/
     2 '   RESP. VALUES OF J, YP, Y(1), Y(JYT), JYT ='/9X,I5,3F9.4,I8)
      RETURN
      END
C
C ****************** >>> SINGLE INTERPOLATION ROUTINE <<< ***************
```

```
C *                                                                   *
C     XY  IS A TABLE OF Y(1),X(1),Y(2),X(2),........Y(NN),X(NN)       *
C     XX  IS THE GIVEN VALUE FOR X                                    *
C     NN  IS IS THE NUMBER OF PAIRS OF ENTERIES IN XY                 *
C     KK  IS BOTH THE POSITION GUESS AND THE FINAL VALUE              *
C*                                                                    *
C *********************************************************************
C
      FUNCTION POLATE (XY,XX,NN,KK)
      DIMENSION XY(2)
      REAL*8 XY,XX,X
      INTEGER*2 NN,KK,N,M,K
      DATA ZERO/0.E0/,NERR/0/
      X = XX
      N = NN
      M = IABS(N)
      K = KK
      IF (K .LT. 1) THEN
                  K = 1
      ELSEIF (K .GT. M) THEN
                  K = M
      ENDIF
C
C     IS CONSTANT WANTED
      IF (M-1) 305,306,310
  305 POLATE = ZERRO
      RETURN
  306 POLATE = XY(1)
      RETURN
C
C     LOOP TO DECREASE THE INDEX
  310 IF (XY(2*K)-X) 320,320,311
  311 K = K - 1
      IF (K) 330,330,310
C
C     LOOP TO INCREASE INDEX
  320 IF (X-XY(2*K+2)) 400,400,321
  321 K = K + 1
      IF (K-M) 320,340,340
C
C     TEST FOR EXTRAPOLATION
  330 IF (N) 331,305,480
  331 K = 1
      GOTO 400
  340 IF (N) 341,305,490
  341 K = M - 1
C
C     GET ANSWER
  400 KK = K
      POLATE = XY(2*K-1) + (X-XY(2*K)) * (XY(2*K+1)-XY(2*K-1))
     1                                 / (XY(2*K+2)-XY(2*K))
      RETURN
C
C     POLATE FAILURE, SEARCH OUT OF BOUNDS
  480 POLATE = XY(1)
      GOTO 500
  490 POLATE = XY(2*M-1)
  500 NERR = NERR +1
      IF (NERR.GT.10) RETURN
      WRITE (2,510) KK,K,N,X,(XY(2*I),I=1,N)
```

```
      IF (NERR.EQ.10) THEN
                    WRITE (2,511)
      ENDIF
      RETURN
 510  FORMAT (16H1ERROR IN POLATE / 16H0INITIAL INDEX =,I6,10X,
     1 13HFINAL INDEX =,I6, 10X,14HARRAY LENGHT =,I6/ 10X,
     2 10HARGUMENT =, E14.6/ 20H0TABLE OF X VALUES = / (4E15.6))
 511  FORMAT (' ERROR PRINTOUT ON POLATE ERRORS ARE SUPPRESSED')
C
      RETURN
      END
C
C ***************************************************************************
```

Table B.2. Results of ADPUMP Sample Run

ADSORPTION PUMP DESIGN

GIVEN PARAMETERS

HEAT SWITCH :

1)DIAMETER =.5080E+01 CM
2)FIN ARREA =.1595E+03 CM
3)SUPPORT TUBE LENGHT =.3810E+01
4)GAP WIDTH =.5080E-02 CM
5)BOTTOM GAP =.1016E-01 CM
6)SIDE GAP =.1016E-01 CM

PUMP :

7)DAIAMETER =.1384E+01 CM
8)LENGHT =.3480E+01 CM
9)WALL THICK. = .2032E+00 CM
10)GAS LINE DIAMETER =.2921E+00 CM
11)GAS LINE LENGHT = .5715E+01 CM
12)MATERIAL = CU
13)HEAT LINK RESISTANCE = .3839E+02 K/W
14)SINK TEMPERATURE = .8100E+01
15)HIGH TEMP. =.4000E+02 K
16)LOW TEMP. =.7000E+01 CM
17)HIGH PRESS. = .1000E+02 TORR
18)LOW PRESS. =.1000E-05 TORR
19)GAS = HELIUM
20)CHARCOAL DENSITY = .5000E+00 gr/cc
21)SOLID CHRCL. DENS. = .2000E+01 gr/cc
22)ADSORP. MATERIAL = CHARCOAL

OUTPUT

GAS VOLUME IN cc

CIRCUMFERENTIAL GAP = .6178E+00
TOP & BOTTOM GAPS = .2059E+00
FIN GAP = .8101E+00
LINE VOLUME = .3830E+00
PUMP VOLUME = .5237E+01
PUMP GAS VOLUME = .5227E+01
LOW GAS DENSITY = .9169E-11 cc/g
HIGH GAS DENSITY = .1605E-04 cc/g

HEAT IN JOULS

LOW ADSORPTION RATIO = .2573E-01
HIGH ADSORPTION RATIO = .1751E-01
ADSORPTION RATIO = .8214E-02
DESORPTION HEAT = .3048E+00
STRUCTURAL HEAT = .2089E+02
CHARCOAL HEAT = .8101E-02
GAS HEAT = .3005E-01
MASS OF PUMP = .3296E+02 gr.

```
************************************
*                                  *
*   TOTAL VOLUME    = .1081E+02 cc *
* MASS OF CHARCOAL = .2118E-01 gr. *
* SWITCH UP ENERGY = .2124E+02  J  *
*   HEAT  LOSS      = .8309E+00  W *
*                                  *
************************************
```

APPENDIX C

HSCONTROL: A CONTROL AND DATA ACQUISITION PROGRAM

This program is stored on the HP 3.5 inch floppy disk which is run on the Hewlett Packard 87XM computer. After inserting the disk, the program is loaded onto the memory by typing

Load "HSCONTROL" <RETURN>

Then, by pressing the <RUN> key, the program is executed and the questions shown in Table C.1 will start to appear on the screen.

At the beginning of the program the user is asked to enter the run number. Then, the date and time are inputted by using DD/MM/YY and HH:MM formats, respectively. The user is then asked to input the voltages and temperature limits for each region. There is no temperature setting for the hot side, since the temperature varies with different head loads. The user is then asked to input the temperature range of the heat switch and the sensor of the hot side, since the calibration routine for each temperature range is different. The computer proceeds to display the initial conditions of the four regions which include the measured temperatures and the calculated power input.

The user is asked to input the time interval in which the data are to be displayed. Since the time for each scan is ten seconds, the data could be displayed in multiples of ten second intervals (e.g., 10, 20, 60) By pressing any number, the data scanning will be activated and the data will be displayed.

At the end of each data scanning cycle, the program executes the temperature control subroutine.

At the specified time interval, the following parameters will be displayed on the screen:

TIME	=	Time after the start of the experiment in seconds
Thot	=	Temperature of the hot side in K
Qhot	=	Power input onto the hot side in W
Tcold	=	Temperature of the cold side in K
Qcold	=	Power input onto the cold side in W
Tpump	=	Temperature of the pump in K
Qpump	=	Power input onto the pump in W

Tsink = Temperature of the pump sink in K

Qsink = Power input onto the pump sink in W

K = Conductance in W/K

This conductance K is calculated by

$$K = Qhot/(Thot-Tcold)$$

This K parameter is also printed on the printer as the time progresses.

When the temperatures reach their steady state, the data acquisition for that particular experimental run can be terminated by the special function key. The program will ask two more questions (as shown in Table C.1) as to whether the user would like to start another experimental run and to store the data on a 3.5-inch floppy disk. If the answer to the second question is positive, a data file is created and the data are stored sequentially.

The example shown in Table C.1 involves the case where the feedback loop was suppressed. The example shown in Table C.2 demonstrates the use of the feedback loop to keep the pump temperature at 142.71 K with a power input of 0.09 W. The example shown in Table C.3 demonstrates that the temperatures of the cold side and the pump bases can be kept at 8.23 and 8.07 ± 0.01 K with 1.79 W power and with 1.6 W power, respectively.

Table C.1. HSCONTROL Demonstration with No Feedback Loop

```
RUN
                        PROGRAM HSCONTROL

              HEAT SWITCH DATA ACQUISITION & CONTROL


PLEASE ENTER THE RUN NUMBER.
Q

ENTER TODAY'S DAY AND TIME (DD/MM/YY,HH:MM)
?
8/13/86,14:00
INPUT THE VOLTAGE (V) FOR THE HOT SIDE.
?
1.34
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE COLD SIDE
?
0,4.8
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP SINK
?
0,4.2
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP
?
0,6
                        ENVIRONMENT  SETTING

HEAT SWITCH PUMP USES Si SENSOR AT ALL SETTINGS FOR TEMP. MEASURMENT
H.S.  PUMP SINK USES Ge SENSOR AT ALL SETTINGS (NOT VALID > 100K)


LN2 RANGE  (77 ----> 120 K):
LHE RANGE  (4  ---->  40 K):
HOT SIDE AND COLD SIDE USE   Ge SENSORS


RM TEMP RANGE  (4  ----> 350 K):
HOT SIDE AND COLD SIDE USE  Si SENSORS FOR TEMPERATURE MEASURMENTS


                              OPTIONS

    1) HS IN LN2 & PUMP IN LHe            3) HS IN LN2 & PUMP IN LN2
    2) HS IN LHe & PUMP IN LHe            4) HS IN LHe & PUMP IN LN2
                      5)  RM TEMP TEST

ENTER YOUR CHOICE (1 TO 5)
?
5
```

EXPERIMENT # 0

TODAY'S DATE = 8/13/86 TIME = 2.00

HEAT SWITCH TEST
4 REGION CONTROL

INITIAL CONDITIONS:

TIME	Thot	Qhot	Tcold	Qcold	Tpump	Qpump	Tsink	Qsink
0.0	52.93	1.78E-001	4.88	0.00	6.06	0.00	4.18	0.0

FEED BACK LOOP = OFF

ENTER THE TIME INTERVAL IN WHICH THE DATA WILL BE RECORDED.
(IN 10 SEC. INTERVALS, FOR EXAMPLE 10,30,60)
?
60

ENTER ANY NUMBER WHEN READY TO START THE EXPERIMENT.
?
1

TIME	Thot	Qhot	Tcold	Qcold	Tpump	Qpump	Tsink	Qsink	K
1.0	76.52	1.65E-001	4.88	.00	6.06	.00	4.18	.0	2.30E-003
2.0	76.54	1.65E-001	4.88	.00	6.07	.00	4.18	.0	2.30E-003
3.0	76.52	1.65E-001	4.88	.00	6.07	.00	4.18	.0	2.30E-003
4.0	76.52	1.65E-001	4.88	.00	6.07	.00	4.18	.0	2.30E-003
5.0	76.54	1.65E-001	4.88	.00	6.06	.00	4.18	.0	2.30E-003
6.0	76.54	1.65E-001	4.88	.00	6.06	.00	4.18	.0	2.30E-003
7.0	76.54	1.65E-001	4.89	.00	6.07	.00	4.18	.0	2.30E-003
8.0	76.54	1.65E-001	4.89	.00	6.06	.00	4.18	.0	2.30E-003
9.0	76.56	1.65E-001	4.89	.00	6.07	.00	4.18	.0	2.30E-003
10.0	76.54	1.65E-001	4.89	.00	6.07	.00	4.18	.0	2.30E-003
11.0	76.56	1.65E-001	4.90	.00	6.06	.00	4.18	.0	2.30E-003
12.0	76.54	1.65E-001	4.90	.00	6.07	.00	4.18	.0	2.30E-003
13.0	76.54	1.65E-001	4.91	.00	6.06	.00	4.18	.0	2.30E-003
14.0	76.54	1.65E-001	4.93	.00	6.07	.00	4.18	.0	2.30E-003
15.0	76.56	1.65E-001	4.95	.00	6.07	.00	4.18	.0	2.30E-003
16.0	76.56	1.65E-001	4.99	.00	6.07	.00	4.18	.0	2.30E-003
17.0	76.56	1.65E-001	5.03	.00	6.07	.00	4.18	.0	2.30E-003
18.0	76.56	1.65E-001	5.08	.00	6.07	.00	4.18	.0	2.31E-003
19.0	76.56	1.65E-001	5.13	.00	6.07	.00	4.18	.0	2.31E-003
20.0	76.56	1.65E-001	5.20	.00	6.07	.00	4.18	.0	2.31E-003
21.0	76.56	1.65E-001	5.26	.00	6.07	.00	4.18	.0	2.31E-003
22.0	76.56	1.65E-001	5.35	.00	6.07	.00	4.18	.0	2.31E-003
23.0	76.56	1.65E-001	5.42	.00	6.07	.00	4.18	.0	2.31E-003
24.0	76.56	1.65E-001	5.49	.00	6.07	.00	4.18	.0	2.32E-003
25.0	76.58	1.65E-001	5.54	.00	6.07	.00	4.18	.0	2.32E-003
26.0	76.58	1.65E-001	5.59	.00	6.07	.00	4.18	.0	2.32E-003
27.0	76.58	1.65E-001	5.63	.00	6.07	.00	4.18	.0	2.32E-003
28.0	76.58	1.65E-001	5.68	.00	6.07	.00	4.18	.0	2.32E-003
29.0	76.58	1.65E-001	5.73	.00	6.07	.00	4.18	.0	2.32E-003
30.0	76.58	1.65E-001	5.78	.00	6.07	.00	4.18	.0	2.33E-003
31.0	76.58	1.66E-001	5.84	.00	6.07	.00	4.18	.0	2.35E-003
32.0	76.58	1.65E-001	5.90	.00	6.07	.00	4.18	.0	2.33E-003
33.0	76.60	1.65E-001	5.97	.00	6.07	.00	4.18	.0	2.33E-003
34.0	76.60	1.65E-001	6.05	.00	6.07	.00	4.18	.0	2.33E-003
35.0	76.60	1.65E-001	6.14	.00	6.07	.00	4.18	.0	2.34E-003
36.0	76.60	1.65E-001	6.25	.00	6.07	.00	4.18	.0	2.34E-003
37.0	76.60	1.65E-001	6.35	.00	6.07	.00	4.18	.0	2.34E-003
38.0	76.60	1.65E-001	6.44	.00	6.07	.00	4.18	.0	2.35E-003
39.0	76.60	1.65E-001	6.52	.00	6.07	.00	4.18	.0	2.35E-003
40.0	76.60	1.65E-001	6.59	.00	6.07	.00	4.18	.0	2.35E-003
41.0	76.60	1.65E-001	6.67	.00	6.07	.00	4.18	.0	2.35E-003
42.0	76.63	1.65E-001	6.74	.00	6.06	.00	4.18	.0	2.36E-003
43.0	76.63	1.65E-001	6.81	.00	6.07	.00	4.18	.0	2.36E-003
44.0	76.60	1.65E-001	6.87	.00	6.07	.00	4.18	.0	2.36E-003
45.0	76.63	1.65E-001	6.94	.00	6.07	.00	4.18	.0	2.36E-003
46.0	76.63	1.65E-001	7.01	.00	6.06	.00	4.18	.0	2.36E-003
47.0	76.60	1.65E-001	7.08	.00	6.07	.00	4.18	.0	2.37E-003
48.0	76.63	1.65E-001	7.15	.00	6.07	.00	4.18	.0	2.37E-003
49.0	76.63	1.65E-001	7.21	.00	6.07	.00	4.18	.0	2.37E-003
50.0	76.63	1.65E-001	7.28	.00	6.07	.00	4.18	.0	2.37E-003

```
IS THIS PROGRAM GOING TO CONTINUE?(KEEP CURRENT VOLTAGES)
?
0
FINISHED
WOULD YOU WANT TO STORE THE DATA ON EXPO ?(1=YES)
?
1
END OF PROGRAM HSCONTROL
```

Table C.2. HSCONTROL Demonstration with Temperature Control at the Adsorption Pump

```
RUN
                              PROGRAM HSCONTROL

          HEAT SWITCH DATA ACQUISITION & CONTROL


PLEASE ENTER THE RUN NUMBER.
?
77

ENTER TODAY'S DAY AND TIME (DD/MM/YY,HH:MM)
?
4/15/86,11:45
INPUT THE VOLTAGE (V) FOR THE HOT SIDE.
?
15.5
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE COLD SIDE
?
0,78
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP SINK
?
0,120
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP
?
3.5,143
                              ENVIRONMENT  SETTING

 HEAT SWITCH PUMP USES Si SENSOR AT ALL SETTINGS FOR TEMP. MEASURMENT
 H.S.  PUMP SINK USES Ge SENSOR AT ALL SETTINGS (NOT VALID > 100K)


 LN2 RANGE  (77 ----> 120 K):
 LHE RANGE  (4  ---->  40 K):
 HOT SIDE AND COLD SIDE USE   Ge SENSORS


 RM TEMP RANGE  (4  ----> 350 K):
 HOT SIDE AND COLD SIDE USE  Si SENSORS FOR TEMPERATURE MEASURMENTS


                                    OPTIONS

      1) HS IN LN2 & PUMP IN LHe           3) HS IN LN2 & PUMP IN LN2
      2) HS IN LHe & PUMP IN LHe           4) HS IN LHe & PUMP IN LN2
                           5)  RM TEMP TEST

ENTER YOUR CHOICE (1 TO 5)
?
3
```

EXPERIMENT # 77

TODAY'S DATE = 4/15/86 TIME = 11:45

4 REGION CONTROL

INITIAL CONDITIONS:

TIME	Thot	Qhot	Tcold	Qcold	Tpump	Qpump	Tsink	Qsink
0.0	79.11	2.49E+000	78.68	0.00	141.81	.09	18.74	0.00

FEED BACK LOOP = ON

ENTER THE TIME INTERVAL IN WHICH THE DATA WILL BE RECORDED.
(IN 10 SEC. INTERVALS, FOR EXAMPLE 10,30,60)
?
60

ENTER ANY NUMBER WHEN READY TO START THE EXPERIMENT.
?
1

ORIGINAL PAGE IS
OF POOR QUALITY

TIME	Thot	Qhot	Tcold	Qcold	Tpump	Qpump	Tsink	Qsink	K
1.0	79.11	2.52E+000	78.68	.00	141.76	.09	18.74	.0	5.86E+00
2.0	79.11	2.52E+000	78.68	.00	141.77	.10	18.74	.0	5.86E+00
3.0	79.11	2.52E+000	78.68	.00	141.82	.10	18.74	.0	5.86E+00
4.0	79.09	2.52E+000	78.68	.00	141.91	.10	18.74	.0	6.16E+00
5.0	79.11	2.52E+000	78.68	.00	142.02	.10	18.74	.0	5.86E+00
6.0	79.11	2.52E+000	78.68	.00	142.01	.09	18.74	.0	5.86E+00
7.0	79.11	2.52E+000	78.68	.00	141.93	.09	18.74	.0	5.86E+00
8.0	79.11	2.52E+000	78.68	.00	141.88	.09	18.74	.0	5.86E+00
9.0	79.11	2.52E+000	78.68	.00	141.87	.09	18.74	.0	5.86E+00
10.0	79.11	2.52E+000	78.68	.00	141.89	.10	18.74	.0	5.86E+00
11.0	79.09	2.52E+000	78.68	.00	141.96	.10	18.74	.0	6.16E+00
12.0	79.11	2.52E+000	78.68	.00	142.02	.10	18.74	.0	5.86E+00
13.0	79.11	2.52E+000	78.68	.00	142.09	.10	18.74	.0	5.79E+00
14.0	79.11	2.52E+000	78.68	.00	142.16	.10	18.74	.0	5.86E+00
15.0	79.11	2.52E+000	78.68	.00	142.23	.10	18.74	.0	5.86E+00
16.0	79.09	2.52E+000	78.68	.00	142.30	.10	18.74	.0	6.08E+00
17.0	79.11	2.52E+000	78.68	.00	142.37	.10	18.74	.0	5.79E+00
18.0	79.11	2.52E+000	78.68	.00	142.44	.10	18.74	.0	5.86E+00
19.0	79.09	2.52E+000	78.68	.00	142.51	.10	18.74	.0	6.16E+00
20.0	79.09	2.52E+000	78.68	.00	142.58	.10	18.74	.0	6.16E+00
21.0	79.09	2.52E+000	78.68	.00	142.65	.10	18.74	.0	6.08E+00
22.0	79.11	2.52E+000	78.68	.00	142.72	.10	18.74	.0	5.86E+00
23.0	79.11	2.52E+000	78.68	.00	142.79	.10	18.74	.0	5.79E+00
24.0	79.09	2.52E+000	78.68	.00	142.85	.10	18.74	.0	6.08E+00
25.0	79.11	2.52E+000	78.68	.00	142.90	.09	18.74	.0	5.86E+00
26.0	79.11	2.52E+000	78.68	.00	142.90	.09	18.74	.0	5.79E+00
27.0	79.09	2.52E+000	78.68	.00	142.87	.09	18.74	.0	6.08E+00
28.0	79.11	2.52E+000	78.68	.00	142.84	.09	18.74	.0	5.79E+00
29.0	79.11	2.52E+000	78.68	.00	142.81	.09	18.74	.0	5.79E+00
30.0	79.09	2.52E+000	78.68	.00	142.79	.09	18.74	.0	6.08E+00
31.0	79.09	2.52E+000	78.68	.00	142.77	.09	18.74	.0	6.08E+00
32.0	79.11	2.52E+000	78.68	.00	142.75	.09	18.74	.0	5.79E+00
33.0	79.09	2.52E+000	78.68	.00	142.74	.09	18.74	.0	6.08E+00
34.0	79.11	2.52E+000	78.68	.00	142.72	.09	18.74	.0	5.79E+00
35.0	79.11	2.52E+000	78.68	.00	142.71	.09	18.74	.0	5.79E+00
36.0	79.09	2.52E+000	78.68	.00	142.71	.09	18.74	.0	6.08E+00
37.0	79.09	2.52E+000	78.68	.00	142.71	.09	18.74	.0	6.08E+00
38.0	79.09	2.52E+000	78.68	.00	142.71	.09	18.74	.0	6.08E+00
39.0	79.09	2.52E+000	78.68	.00	142.71	.09	18.74	.0	6.08E+00
40.0	79.09	2.52E+000	78.68	.00	142.71	.09	18.74	.0	6.08E+00

IS THIS PROGRAM GOING TO CONTINUE?(KEEP CURRENT VOLTAGES)
?
0
FINISHED
WOULD YOU WANT TO STORE THE DATA ON EXP77?(1=YES)
?
1

END OF PROGRAM HSCONTROL

Table C.3. HSCONTROL Demonstration with Temperature Controls at the Cold Side of the Heat Switch and at the Pump Base

```
RUN
                         PROGRAM HSCONTROL

         HEAT SWITCH DATA ACQUISITION & CONTROL



?
70

ENTER TODAY'S DAY AND TIME (DD/MM/YY,HH:MM)
?
4/8/86,11:30
INPUT THE VOLTAGE (V) FOR THE HOT SIDE.
?
0.85
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE COLD SIDE
?
4,8.2
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP SINK
?
5,8
INPUT THE INITIAL VOLTAGE(V) AND FINAL TEMPERATURE(K) FOR THE PUMP
?
0,10
                         ENVIRONMENT  SETTING

 HEAT SWITCH PUMP USES Si SENSOR AT ALL SETTINGS FOR TEMP. MEASURMENT
 H.S.  PUMP SINK USES Ge SENSOR AT ALL SETTINGS (NOT VALID > 100K)


 LN2 RANGE  (77 ----> 120 K):
 LHE RANGE  (4  ---->  40 K):
 HOT SIDE AND COLD SIDE USE   Ge SENSORS


 RM TEMP RANGE  (4  ----> 350 K):
 HOT SIDE AND COLD SIDE USE  Si SENSORS FOR TEMPERATURE MEASURMENTS


                              OPTIONS

     1) HS IN LN2 & PUMP IN LHe          3) HS IN LN2 & PUMP IN LN2
     2) HS IN LHe & PUMP IN LHe          4) HS IN LHe & PUMP IN LN2
                         5)  RM TEMP TEST

ENTER YOUR CHOICE (1 TO 5)
?
2
```

EXPERIMENT # 70

TODAY'S DATE = 4/87/86 TIME = 11:30

HEAT SWITCH TEST
4 REGION CONTROL

INITIAL CONDITIONS:

TIME	Thot	Qhot	Tcold	Qcold	Tpump	Qpump	Tsink	Qsink
0.0	5.81	6.97E-003	4.21	.76	7.69	0.00	4.26	.40

FEED BACK LOOP = ON

ENTER THE TIME INTERVAL IN WHICH THE DATA WILL BE RECORDED.
(IN 10 SEC. INTERVALS, FOR EXAMPLE 10,30,60)
?
10

ENTER ANY NUMBER WHEN READY TO START THE EXPERIMENT.
?
1

ORIGINAL PAGE IS
OF POOR QUALITY

TIME	Thot	Uhot	Tcold	Ucold	Tpump	Upump	Tsink	Usink	K
10.0	6.48	6.97E-003	6.33	.76	8.26	.00	5.52	.4	4.51E-002
20.0	6.56	6.96E-003	6.33	.76	8.37	.00	5.53	.4	3.07E-002
30.0	6.62	6.93E-003	6.33	.76	8.41	.00	5.53	.4	2.40E-002
40.0	6.68	6.92E-003	6.33	.76	8.43	.00	5.54	.4	1.98E-002
50.0	6.74	6.91E-003	6.33	.76	8.42	.00	5.50	.4	1.68E-002
60.0	6.80	6.94E-003	6.33	.76	8.41	.00	5.50	.4	1.48E-002
70.0	6.86	6.96E-003	6.33	.76	8.41	.00	5.50	.4	1.32E-002
80.0	6.92	6.96E-003	6.33	.76	8.41	.00	5.50	.4	1.20E-002
90.0	6.97	6.96E-003	6.33	.76	8.41	.00	5.50	.4	1.09E-002
100.0	7.45	6.96E-003	7.59	1.44	8.80	.00	7.29	1.2	-.49E-001
110.0	7.76	6.96E-003	7.66	1.44	9.32	.00	7.30	1.2	6.70E-002
120.0	7.86	6.97E-003	7.67	1.44	9.67	.00	7.87	1.5	3.61E-002
130.0	8.06	6.98E-003	8.03	1.67	9.91	.00	7.88	1.5	2.90E-002
140.0	8.22	6.97E-003	8.05	1.67	10.05	.00	8.03	1.6	4.08E-002
150.0	8.35	6.97E-003	8.17	1.75	10.14	.00	8.04	1.6	4.03E-002
160.0	8.46	6.97E-003	8.22	1.78	10.20	.00	8.08	1.6	2.82E-002
170.0	8.56	6.97E-003	8.23	1.78	10.23	.00	8.08	1.6	2.07E-002
180.0	8.65	6.97E-003	8.23	1.78	10.25	.00	8.09	1.7	1.65E-002
190.0	8.74	6.97E-003	8.23	1.78	10.26	.00	8.09	1.7	1.37E-002
200.0	8.83	6.97E-003	8.23	1.78	10.27	.00	8.09	1.7	1.17E-002
210.0	8.91	6.98E-003	8.23	1.78	10.27	.00	8.09	1.7	1.03E-002
220.0	8.99	6.98E-003	8.23	1.78	10.27	.00	8.09	1.7	9.14E-003
230.0	9.08	6.98E-003	8.23	1.78	10.28	.00	8.09	1.7	8.22E-003
240.0	9.16	6.98E-003	8.23	1.78	10.27	.00	8.07	1.6	7.47E-003
250.0	9.25	6.98E-003	8.23	1.79	10.27	.00	8.07	1.6	6.87E-003
260.0	9.33	6.96E-003	8.23	1.79	10.26	.00	8.07	1.6	6.32E-003
270.0	9.41	6.98E-003	8.23	1.79	10.26	.00	8.07	1.6	5.90E-003
280.0	9.50	6.97E-003	8.23	1.79	10.26	.00	8.07	1.6	5.50E-003
290.0	9.58	6.98E-003	8.23	1.79	10.26	.00	8.07	1.6	5.17E-003
300.0	9.66	6.99E-003	8.23	1.79	10.26	.00	8.08	1.6	4.87E-003
310.0	9.75	7.00E-003	8.23	1.79	10.26	.00	8.08	1.6	4.61E-003
320.0	9.83	6.98E-003	8.23	1.79	10.26	.00	8.07	1.6	4.37E-003
330.0	9.91	6.96E-003	8.23	1.79	10.26	.00	8.07	1.6	4.14E-003
340.0	9.99	6.96E-003	8.23	1.79	10.26	.00	8.07	1.6	3.95E-003
350.0	10.07	6.96E-003	8.23	1.79	10.26	.00	8.08	1.6	3.77E-003
360.0	10.15	6.96E-003	8.23	1.79	10.26	.00	8.08	1.6	3.61E-003
370.0	10.23	6.95E-003	8.23	1.79	10.26	.00	8.08	1.6	3.47E-003
380.0	10.31	6.96E-003	8.23	1.79	10.26	.00	8.08	1.6	3.34E-003
390.0	10.39	6.99E-003	8.23	1.79	10.26	.00	8.08	1.6	3.23E-003
400.0	10.47	6.98E-003	8.23	1.79	10.26	.00	9.08	1.6	3.12E-003
410.0	10.54	6.98E-003	8.23	1.79	10.26	.00	8.07	1.6	3.02E-003
420.0	10.62	6.99E-003	8.23	1.79	10.25	.00	8.07	1.6	2.92E-003
430.0	10.70	6.98E-003	8.23	1.79	10.25	.00	8.07	1.6	2.83E-003

```
IS THIS PROGRAM GOING TO CONTINUE?(KEEP CURRENT VOLTAGES)
?
0
FINISHED
WOULD YOU WANT TO STORE THE DATA ON EXP70?(1=YES)
?
1
END OF PROGRAM HSCONTROL
```

APPENDIX D
HSINTFC2: A SYSTEM PROGRAM TO COMPUTE HEAT SWITCH INTERFACE PARAMETERS

A computer software program was written in Fortran 77 to compute the temperatures and the heat leaks of a system which involves the heat switches, the redundant cryocoolers, and the cold plates. This program is executed by typing

B:> HSINTFC2 <RETURN>

The menu below appears on the screen and the user is asked to enter the case number. After the three ratios are inputted, the program proceeds with the calculations and then prints out the results in a special format as seen in Fig. D.1. These results are superimposed on the thermal circuit diagram as shown in Fig. D.2 to yield the results as shown in Section 7.0.

```
A>HSINTFC2
                  *****>>> HEAT SWITCH INTERFACE <<<*****

1)   TA = 300.0 K
2)   TO1 = 80.0 K          5)   TL1 = 85.0 K        11)   Q1 = 8.3 W
3)   TO2 = 20.0 K          6)   TL2 = 22.0 K        12)   Q2 = 1.9 W
4)   TO3 =   8.0 K         7)   TL3 =   9.0 K       13)   Q3 =  .3 W

ARE YOU USING THE ABOVE VALUES? (1=YES)
1
ENTER THE CASE NUMBER (UP TO 20 CHARACTERS)
OR TYPE "END" TO FINISH
CASE A
ENTER RATIO3, RATIO2, RATIO1
1.,1.,1.
```

2.05 W 2.09 W

104.54 K/W 105.24 K/W

85.88 K

.60 K/W .60 K/W 9.97 W

107.90 K/W 143.16 K/W

6.71 W

22.59 K

1.05 K/W 1.05 K/W 2.30 W

523.46 K/W 523.45 K/W

1.48 W

9.09 K

3.33 K/W 3.33 K/W .32 W

.27 W

Figure D.1. Computer Printout (Case A)

CASE A

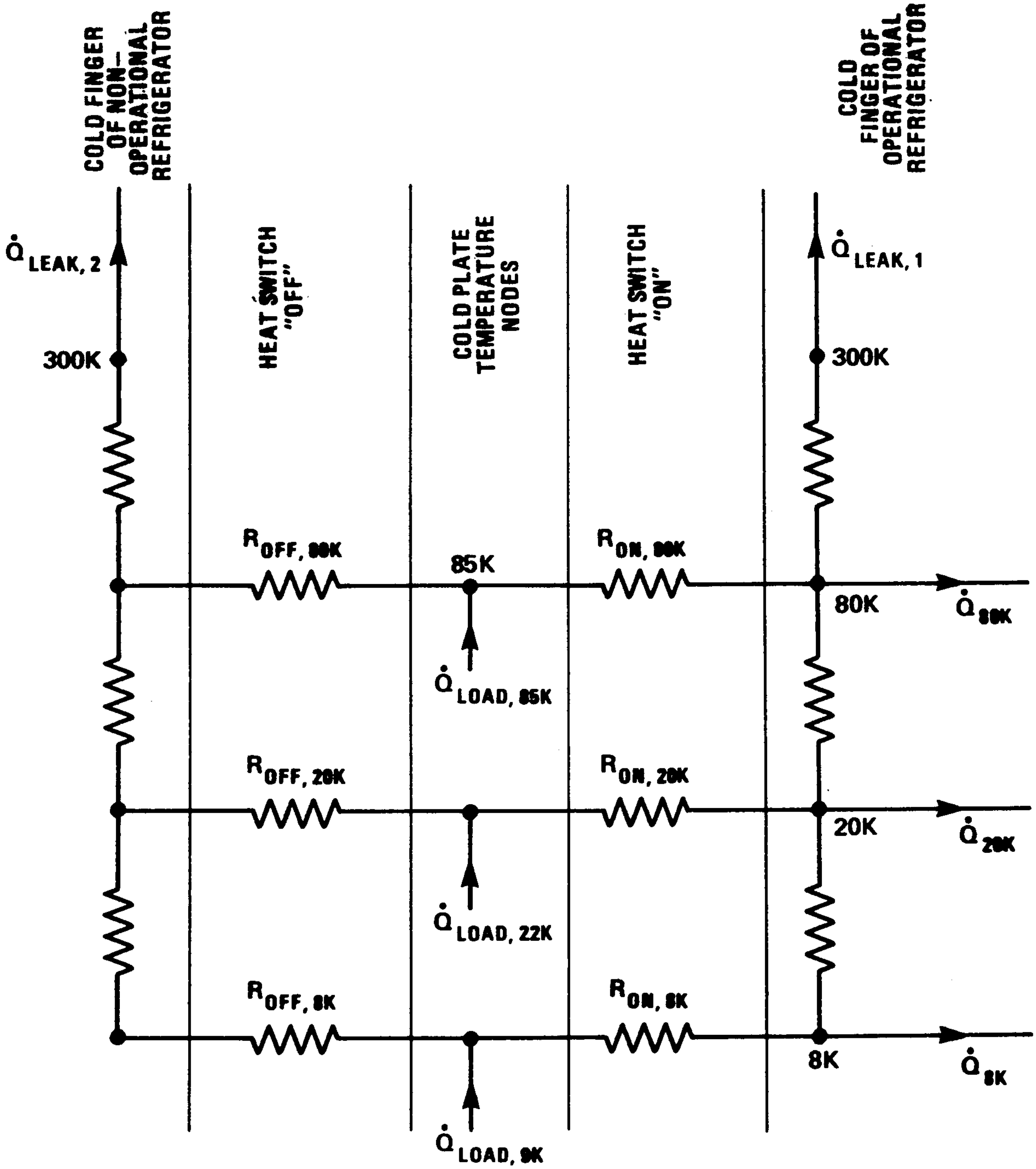

Figure D.2. Thermal Circuit Diagram

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15. Supplementary Notes

16. Abstract

The service life and/or reliability of far-infrared sensors on surveillance satellites is presently limited by the cryocooler. The life and/or reliability, however, can be extended by using redundant cryocoolers. To reduce parasitic heat leak, each stage of the inactive redundant cryocooler must be thermally isolated from the optical system, while each stage of the active cryocooler must be thermally connected to the system. The thermal break or the thermal contact can be controlled by heat switches. Among different physical mechanisms for heat switching, mechanically actuated heat switches tend to have low reliability and, furthermore, require a large contact force. Magnetoresistive heat switches are, except at very low temperatures, of very low efficiency. Heat switches operated by the heat pipe principle usually require a long response time. A sealed gas gap heat switch operated by an adsorption pump has no mechanical motion and should provide the reliability and long lifetime which are required in long-term space missions. Another potential application of a heat switch is the thermal isolation of the optical plane during decontamination.

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